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"ON BONEFORMATION"

ITS RELATION TO TENSION AND PRESSURE

BY

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TO MY
HIGHLY-ESTEEMED FRIEND
SIR ROBERT JONES,
K.B.E., C.B., Ch.M., F.R.C.S.

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PREFACE.

This treatise deals with bone*formation* only. Questions of bone*growth*, which have been often mixed up with boneformation, have been left out of discussion. The interested reader may find reference to them in our study, "Feebleness of Growth and Congenital Dwarfism" which is being published in the Oxford Medical Press.

The knowledge of the effect of mechanical stresses on bone-formation affords the special surgeon a basis for the treatment of disturbances of the form and connection of bones as well as for the eventual choice and use of bone transplants. For the anatomist it determines an insight into the structure and the form of bones. To the natural philosopher it offers an opportunity to recognise factors in living nature which cannot be reduced to mechanical stresses. In bone mechanical stresses seem to be of greater importance than in any other living tissue. Their effect, moreover, can be traced more easily and defined more accurately. For these very reasons bone is more suitable than any other tissue to give evidence of the activity of other non-mechanical agents and even to give some idea as to their relation to the mechanical factors.

If this book may claim a little of this fourfold significance it will be largely due to Dr. J. W. C. Goethart, Director of the Herbarium of Leiden University, who with great skill and inexhaustible patience took the photographs; to Professor and Mrs. J. Clay-Jolles, of the Polytechnic School, Bandoeng, Java, who so willingly gave their help in the solution of mechanical problems; and to Professor John S. B. Stopford, of Manchester, who had the great kindness of correcting and improving the English text. They may ever be sure of the sincere gratitude of

THE AUTHOR.

Leiden,
November, 1920.

INTRODUCTION.

In orthopædic literature the opinion prevails that tension as well as pressure forms a trophic stimulus to bone tissue. Both tension and pressure are said to promote bone formation and even to determine the external form of bones. In the direction of greatest tension and of greatest pressure nature is said to form the elements of the cancellous tissue as if following the rules of graphostatics. Thus the bone elements are considered to cross at right angles (like the directions of greatest tension and greatest pressure which prevail there), *i.e.*, to form insubstantiated stress trajectories.[1]

An investigation into the grounds on which this beautiful and attractive idea was based, gave rise to the following treatise. The reader may judge whether these grounds are tenable, or whether a different opinion concerning the formation of bone as well as the structure and the form of the skeletal parts will have to take the place of the prevailing one.

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[1] Cf f. i. Die trajektoriellen Strukturen von DR. HERMANN TRIEPEL.—Wiesbaden, BERGMANN, 1908.

CHAPTER I.

LITERATURE.

At a meeting of the "naturforschende Gesellschaft" in Zürich, held in the late summer of 1866, H. MEYER, the well-known anatomist, showed a frontal section of the upper part of the femur. Among those present there was also CULMANN, the founder of graphostatics, who observed that the bone elements in the section ran "along the same lines that he had taught his pupils to draw in a crane," *i.e.* in the directions of greatest pressure and greatest tension. In this resemblance we seem to have proof that the plates and bars in the cancellous tissue of bones have formed along the trajectories of stress in it. Through the statical pressure which slightly bends the neck of the femur, and causes tension in its convex and pressure in its concave side, the structure of the femur was considered to coincide with the directions of maximal tension and pressure in a crane. Besides the statical pressure of the body weight, muscle action also causes stresses in the femoral neck which are often greater than those of gravity, and therefore may also have a share in the formation of the bone elements; yet muscle action was excluded from consideration. The resemblance between the trajectories in a crane and the bone elements in the femoral neck was so striking that similarity was taken for identity without any further proof being considered necessary. This is how the theory that tension as well as pressure causes bone formation, made its entry into biology, supported—

as it seemed—by the solid foundations of graphostatics and the combined authority of men like CULMANN and MEYER.

Only a year later (1867) MEYER[1] gave a description of the "Architecture of cancellous tissue" (of the bones of the lower extremity) in which all elements that did not directly bear the body weight, were without further argument described as tension elements. Yet a difference between his schematic representations of the cancellous tissue and the trajectories in technical structures did not escape MEYER's attention.

The trajectories in a crane cross indeed at right angles, because in elastic bodies the directions of greatest tension and pressure cross at right angles. In MEYER's figures, however, the "tension" and the pressure elements cross at oblique angles in the upper end of the femur as well as in the calcaneum, the first metatarsal bone and the patella. (See H. MEYER l.c. Tabelle xvii, Figs. 1, 6 and 8.) From this MEYER ought to have concluded that either the "tension" elements of the cancellous tissue did not coincide with the direction of greatest tension, or that the pressure elements did not coincide with the direction of greatest pressure, or otherwise that neither the "tension" elements correspond with the direction of greatest tension nor the pressure elements with the direction of greatest pressure. MEYER, however, does not mention this fundamental difference between the direction of bone elements in cancellous tissue and that of the trajectories of CULMANN's structures.

In 1892 this difficulty seemed to be removed by JULIUS WOLFF in *The Law of the Transformation of Bones.* In this beautifully got up quarto WOLFF restricted his investigation to a single part of the skeleton—as he himself states—viz., the upper extremity of the femur (p. 9 l.c.). He alleges that MEYER'S representation of the upper end of the femur is incorrect, because in it the bars of the convex side cross those of the concave side at oblique angles. He declares that the parts of the cancellous tissue cross at right angles, and calls himself the discoverer of "Orthogonality." That "orthogonality" formed the basis of CULMANN-MEYER'S crane hypothesis apparently escaped WOLFF'S attention. With the discovery of "orthogonality" WOLFF claimed to have brought forward mathematical proof that both tension and pressure determine the internal structure (and even the external form) of bones (p. 92 l.c.). He formulates this in his *Law of the Transformation of Bones* in the following terms. "Wheresoever stresses of pressure and tension are caused in a bone, be it by pressing forces or by pulling forces, formation of bone takes place" (p. 88 l.c.).

---

[1] H. MEYER, Die Architectur der Spongiosa. REICHERT u. DUBOIS-REYMOND'S Archiv für Anatomie, 1867.

Meanwhile CULMANN-MEYER-WOLFF'S opinion seemed to be confirmed from another side, viz., by W. ROUX[1], who examined an ankylosed knee joint, the bone elements of which—as he alleged—corresponded exactly with the directions of greatest tension and greatest pressure which he had made visible on plates of rubber, in the form of antero-posterior sections through the ankylosed knee after having covered the rubber plate with a layer of paraffin or stearic acid.

WOLFF and ROUX imagined that they had not only proved the equivalence of pressure and tension to bone formation, but had also given evidence for the assumption that these stresses are the sole and all dominant factor in bone formation. Hence they established the doctrine of the "functional form of bones," according to which not only the structure but also the form of bones is determined entirely, "mechanically" and "mathematically" by tension and pressure stresses. With this doctrine they made their influence felt even on natural philosophy by the assertion—more general still—that "the form of the organs of living beings is determined mechanically, not teleologically." (J. Wolff, l.c. p. 146).

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[1] W. ROUX, Beiträge zur Morphologie der functionellen Anpassung, Beschreibung und Erläuterung einer knöchernen Kniegelenkankylose Archiv. f. Anatomie u. Entwickelungsgeschichte, 1885. blz. 120 ff.

Nor did nomenclature fail to press its stamp on these notions. It is well known that in geometry lines which belong to such a system as Roux made visible on his plates of rubber, and which cross at constant angles, are called trajectories. Hence the lines of greatest tension and pressure which cross at right angles, and which graphostatics taught us to determine by drawing, are "trajectories," works constructed according to these stress lines being "trajectorial structures." So, since proof seemed to have been given that the elements of cancellous bone coincide with the stress trajectories of graphostatics, the denomination "trajectorial structures" was introduced for the various parts of the skeleton. We beg to emphasize once more that this name stands or falls with the constancy of the angle at which these elements cross; so the incorrectness of this denomination will be proved, when further inquiry shall show that the angles at which these elements cross, vary, *i.e.*, are sometimes right, sometimes acute and obtuse.

This is in short the origin and development of the doctrine which attributes both to tension and pressure the power of causing and promoting bone formation, a doctrine which even now after half a century dominates the views of scientists concerning the structure, the formation and the transformation of bone, and which has not failed to make its influence felt in the clinical treatment of bony changes—bone fractures and bone transplantations.

A number of authors have made objections to the Meyer-

WOLFF-ROUX'S view; but their arguments have been brought forward in vain.

ZSCHOKKE[1] in 1892—in a treatise as modest as it is thorough—pointed out that "where there is tension only, *i.e.*, where the ligaments do not press upon a bony surface, but where they are attached to it, *i.e.* at right angles, there is so to speak never a prominence but sooner a groove" (p. 19 l.c.), "that in the deeper parts of the bone there are not always with certainty bony structures in the direction of the pulling ligaments," that furthermore where the points of insertion of the muscles form protrusions "these protrusions do not develop in the direction of the tendons (*i.e.*, of the pull) but at right angles to it" (p. 18 l.c.), that from a "phylogenetic" and an "ontogenetic" point of view it is important to note "that the primary formation of bone occurs only where pressure may be adopted," "while on the other hand the 'tension' elements generally present themselves as ligaments and tendons, *i.e.*, as soft 'tissues' (p. 19, 20 l.c.), and that we are positively obliged to assume that the development of bone depends on a certain degree of pressure in the tissues" (p. 19 l.c.).

SOLGER[2] expressed doubt whether tension does indeed lead to bone formation: "In order to ascertain whether pulling forces, which act upon bone in an entirely regular way, affect the direction of bone elements"—he says—"I cut the arch of a human dorsal vertebra with the associated elastic ligamentum flavum into microscopical sections parallel to the elastic fibres. The result was an absolutely negative one."

BÄHR[3] says; "In all probability . . . . . . the spongiosa answers to real stress curves; however these are, in contradiction to former opinion, not tension and pressure curves, but exclusively pressure curves."

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[1] E. ZSCHOKKE, Weitere Untersuchungen über das Verhältniss der Knochenbildung zur Statik und Mechanik des Vertebraten-Skelettes, Zürich 1892.

[2] B. SOLGER, Der gegenwärtige Stand der Lehre von der Knochen-Architectur, MOLESCHOTT XVI Bd. 1899.

[3] F. BÄHR Betrachtungen über die statischen Beziehungen des Beckens zur unteren Extremität. D. Zeitsch. f. orth. Chir. Bd. V, blz. 55.

E. ALBERT[1], who has furnished a number of accurate contributions to the literature on the morphology of cancellous tissues, says "Against the crane theory such conclusive arguments have been brought forward that from the present state of things no investigator would undertake to raise *considerations* on the ground of this theory regarding the life of bone tissue."

BÜDINGER[2], who carefully examined the cancellous tissue of the bones of the upper extremity, states that they are not built on the principles of technical science.

Nevertheless in addition to MEYER, WOLFF, and ROUX, T. ZAAYER[3], v. RECKLINGHAUSEN[4], KORTEWEG[5], GHILLINI[6], WALKHOFF[7], REVENSTORF[8], and others have ascribed to both tension and pressure, the power of forming bone. Men like HOFFA and KÖNIG have not only adopted WOLFF's views, but also praised his work as a monument to German science. THOMA has used the MEYER-CULMANN'S hypothesis as an established fact, basing on it an attempt to explain the structure of the skull.[1] In short, the skeletal parts have without proof been described as trajectorial structures. The external form and internal architecture of the bones are considered to be the mere result of "pull and pressure acting upon them."[2,3] And even in the latest literature we find WOLFF's "law" quoted as a guide for the selection of transplants of bone in our clinics.[4]

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[1] E. ALBERT, Einführung in das Studium der Architektur der Röhrenknochen, Holder, Wien, 1920.

E. ALBERT, Ueber die Architektur der Knochenspongiosa. W. kl. Wochenschr. 1898, blz. 1907.

E. ALBERT, Die Architektur der Tibia. W. med. Wochensch. 1900, No. 4, 5, 6.

[2] K. BÜDINGER, Der Spongiosabau der oberen Extremität. Zeitsch f. Heilkunde 24 Bd. (Neue Folge 4 Bd.) 1903.

[3] T. ZAAYER, De architectuur der beenderen. Ned. Tijdsch. v. Geneesk. 1871. II blz. 113.

[4] v. RECKLINGHAUSEN, D. med. Wochenschr. 1893, XIX. Jahrg. blz. 507.

[5] J. A. KORTEWEG, Die Ursachen der orthopaed. Knochenmissbildung. D. Zeitsch. f. orth. Chir. Bd. V, blz. 174.

[6] Cesare GHILLINI, Die Pathogenese der Knochendeformitäten. D. Zeitsch. f. orth. Chir., Bd. VI 1899, blz. 590.

[7] O. WALKHOFF, Der Unterkiefer der Anthropomorphen u. des Menschen in seiner Entwickelung u. Gestalt, 1902, in Selenka, Menschenaffen (Anthropomorphæ), Studien über Entwicklung und Schädelbau.

[8] REVENSTORF, Ueber die Transformation der Calcaneusarchitektur. Archiv. f. Entwicklungsmechanik der Organismen v. WILHELM ROUX, 1907, blz. 379.

Thus it is that the hypothesis raised for the upper end of the femur by CULMANN, applied to other bones by MEYER, "established" "mathematically" by WOLFF, "confirmed" anatomically by ROUX, has survived for half a century as a solid corner stone to the building of our sciences, as a means of "instruction in the theory of Mechanics" (J. WOLFF, l.c. p. 147), and as a reliable starting point even for considerations regarding the development of living beings (J. WOLFF, l.c. p. 146).

With a view to test the CULMANN-MEYER-WOLFF-ROUX's dualistic, wide-spread and far-reaching doctrine on bone formation with observations of our own, we sectioned, about 17 years ago, a large number of bones—some normal in form and others curved (rickety), as well as mal-united fractures, some whole skeletons which were held together by their dried ligaments and ankylosed knee, elbow and hip joints. This was done with a thin electric bandsaw, and the most varied directions were chosen. The most instructive of these cuts will be represented in this book, in order to enable the reader to test the CULMANN-MEYER-WOLFF's dualistic doctrine—

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[1] R. THOMA, Ein Beitrag zur Histomechanik des Skelettes u. zur Lehre von dem interstititiellen Knochenwachstum. VIRCHOW's Archiv, 188. Bd., 1907, blz. 303 ff.

R. THOMA, Untersuchungen uber das Schädelwachstum und seine Störungen. VIRCHOW's Archiv, Bd. 206, 1911.—Bd. 212, 1913.—Bd. 219, 1915.—Bd. 223, 1916.—Bd. 224, 1917.

[2] LEON, Ueber technische Anpassungen in der Natur. Zeitschr. des Vereins deutscher Ingenieure. Bd. 62, No. 28, 8 Juni 1918.

[3] L. BOLK, Over kruisschedels, Geneesk. bladen 18de reeks No. XI, blz. 15.

[4] F. A. ALBEE, Bonegraft surgery, W. B. SAUNDERS Co., Philadelphia and New York, 1917.

and with it the different "proofs" for the formation of bone by tension which have been brought forward in literature—with a series of new facts.

The questions to be answered in the first place are:—

(1) Do the elements of cancellous tissue always cross at *right angles? i.e.*, do they coincide with the directions of greatest tension and pressure?

(2) Does cancellous tissue show bone in any part which has to resist *tension only?* and

(3) Do resisting bone elements undergo thickening on an increase of tension, as is the case on an increase of pressure? In short does bone tissue respond to pull in the same way as it does to pressure? *i.e.*, is bone formation equally stimulated by tension as it is by pressure? and in the second place:

Is *all* bone formation dependent on mechanical stresses and do these stresses determine the form of bones entirely and exclusively?

CHAPTER II.

UNTENABILITY OF THE GROUNDS ON WHICH A TROPHIC EFFECT ON BONE HAS BEEN ASCRIBED TO TENSION.

A. In bones formed in cartilage.

1.—The Upper Femoral End.

Before we are entitled to assume that a system of plates or bars in cancellous tissue has been brought about by tension, it must in the first place be considered whether these elements have served to bear pressure during life. That pressure stresses can promote or cause bone formation has been justly agreed upon by every investigator as an established fact. This will become evident to the reader on the mere consideration of the figures in this book. Hence, if upon a system of bone elements both pressure and tension have been acting during life, this system cannot serve as a proof that tension stresses have the power of forming bone. The possibility must be considered that the firm tissue, brought about by pressure, has merely acted as a conductor to the tension stresses, without at the same time receiving a formative or even trophic stimulus from them. This simple truth has been lost sight of by those who ascribed to tension stresses a trophic effect on bone tissue merely in view of the fact that during life certain bone elements had served to resist tension stresses.

If, for example, we may adopt the argument that during life the femoral neck (Fig. 1) was (even though slightly) bent by the body weight and the elements on the convex side were stretched, this does not by any means imply that these elements have been brought about or even strengthened by such tension. The femoral neck has been subjected not only to the static force of the body weight but also to dynamic forces of muscle action; pressure stresses have been caused in the elements of the convex side of the femoral neck by the glutei from the outer side of the trochanter major and the obturator muscles, pyriformis and gemelli from the inner side of the great trochanter. To these a share in the formation of the elements on the convex side cannot be denied, the less so since the dynamic forces may surpass considerably the static ones. So the question whether tension stresses, brought about in the convex side of the femoral neck by the static forces of the body weight, have had a share in the formation of the bone tracts on the convex side, is not answered by the mere coincidence of the direction of these elements with the direction of tension stresses, but demands special investigation. Such investigation has been made by sawing up a number of normal and deformed femoral necks. The structure of these will bring us nearer the answer.

In Fig. 2 the elements of the convex side cross the concave ones at very *oblique* angles. Nor is "orthogonality" shown in Figs. 3, 4 and 5; and even in Fig. 1 it does not seem difficult to point out *oblique* crossings. Differences in the direction of these sections cannot be made responsible for these differences; all preparations have been opened up rather accurately along the axis of the femoral neck or lines parallel to it. So, at various places we find oblique angles of crossing between the bone elements instead of right angles. We directed attention above to the fact that in an elastic deformed body, for instance in

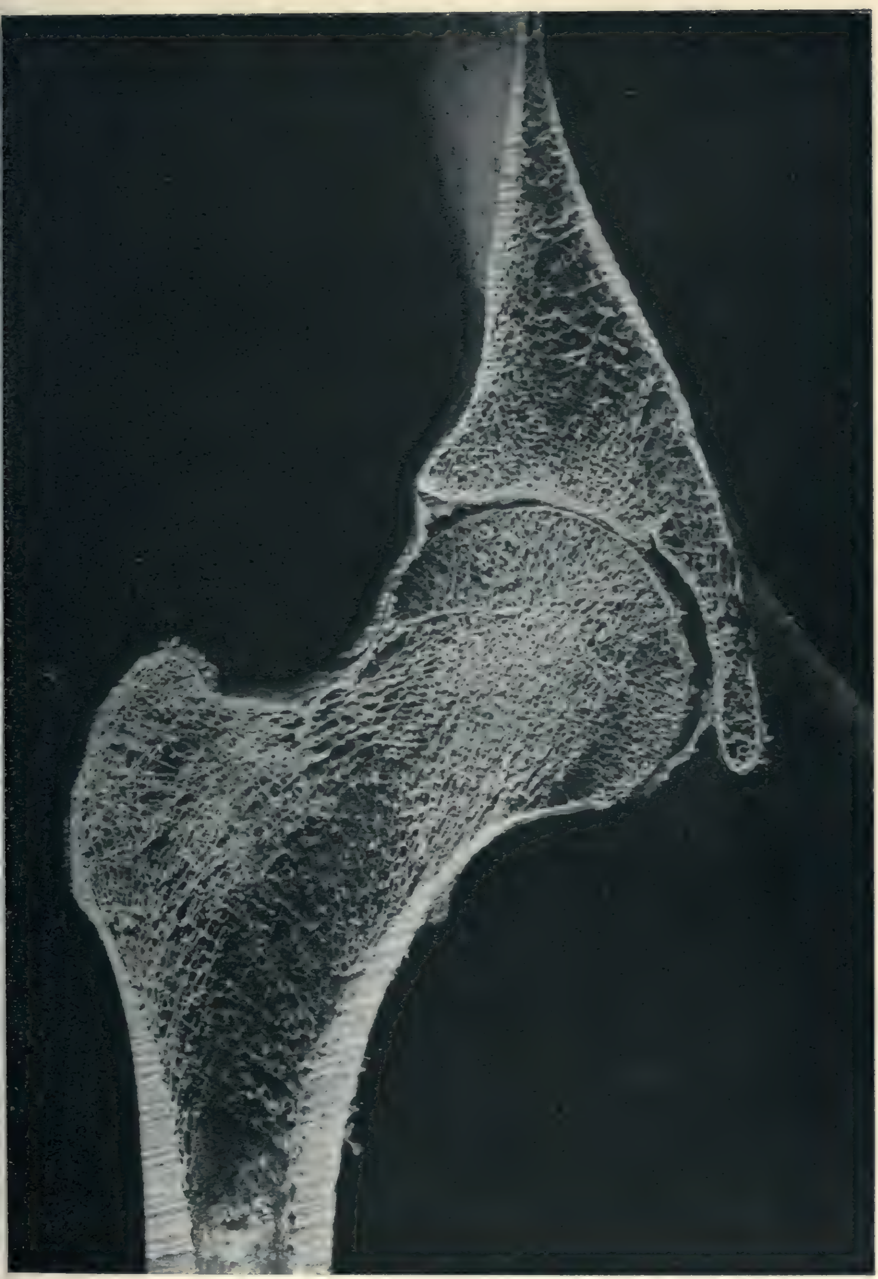

Fig. 1

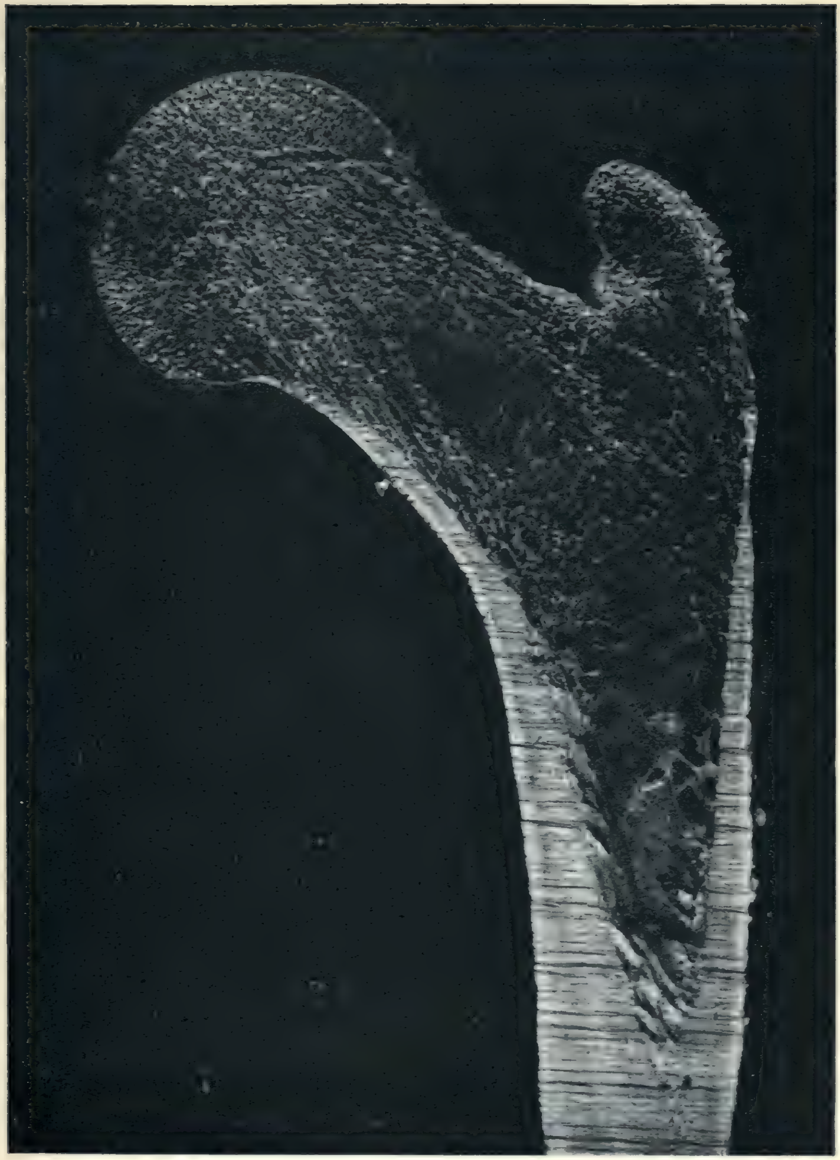

Fig. 2

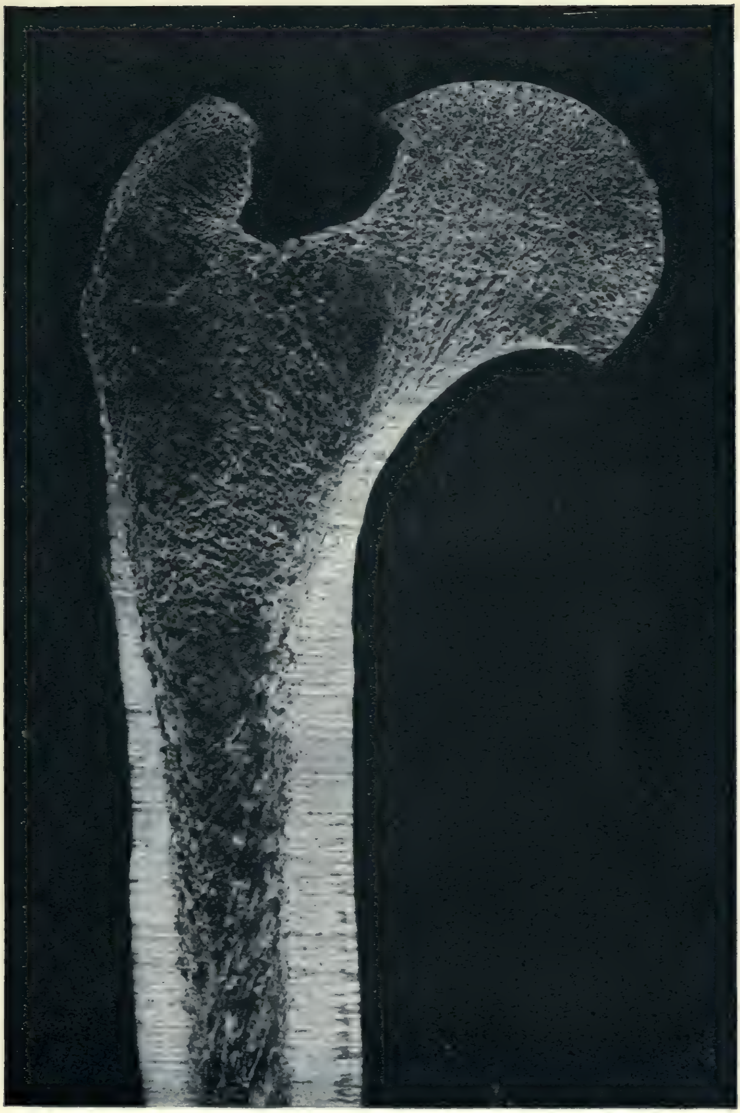

Fig. 3

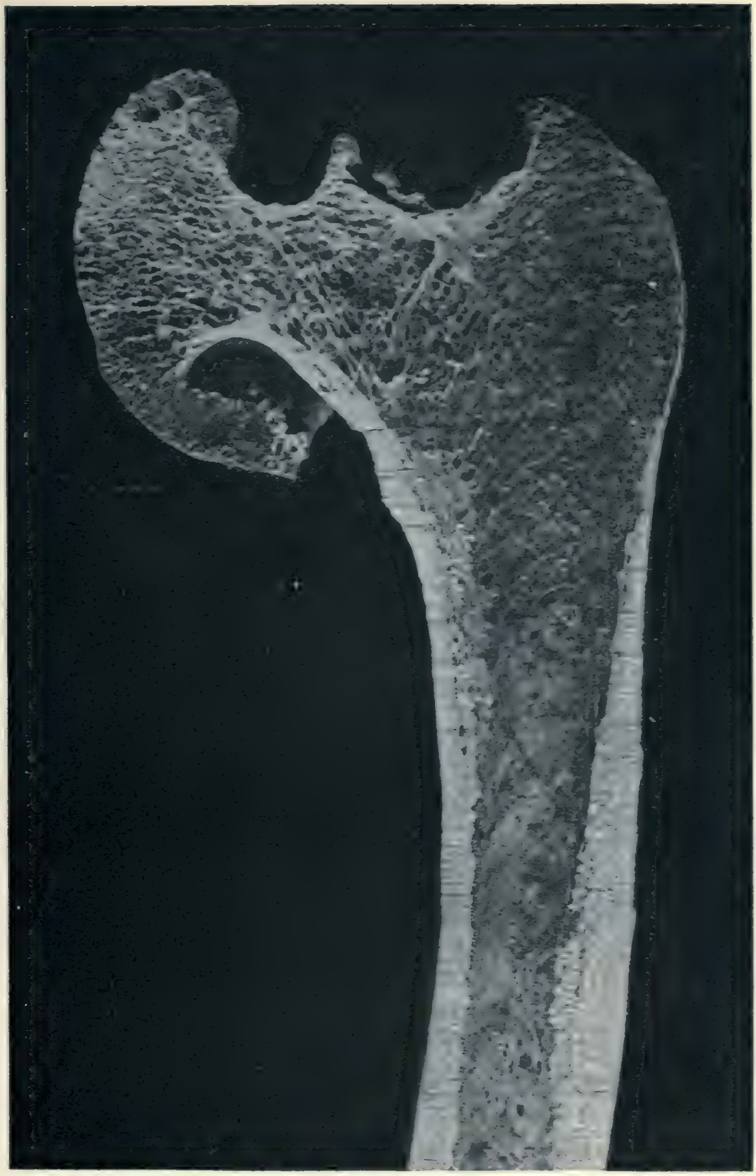

Fig. 4

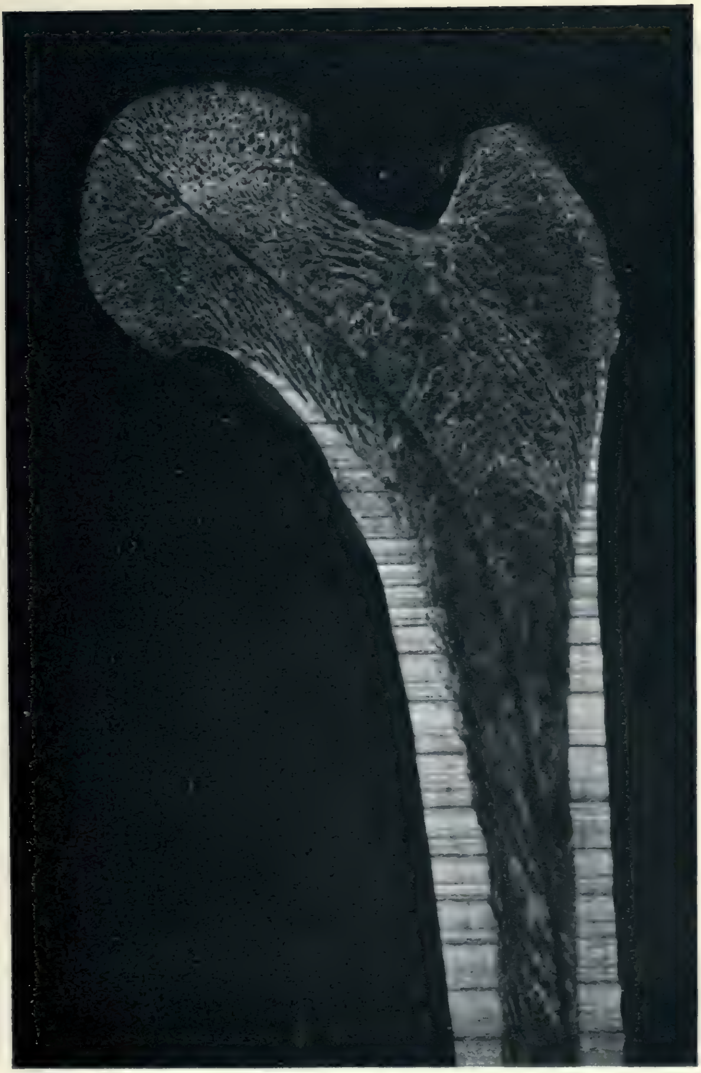

Fig. 5

the shape of a crane, when it is made to bear weight in a certain way, the directions of greatest tension and greatest pressure will cross at right angles. So if we assume that the elements of the concave side correspond with the direction of greatest pressure, the ones of the convex side would make right angles with them, if they did indeed coincide with the direction of greatest pull. But they do not make right angles. Hence the structure of the femoral necks represented does not answer to the CULMANN-MEYER'S hypothesis, and the elements of the convex side must not be considered as coinciding with the direction of greatest tension. Tension stress cannot be considered the stimulus which has either produced or maintained the bone elements of the convex side, and we must search for other stresses which may be made responsible for their formation. But whatever may be the result of such research, it is certain that the *inconstancy of the angles of crossing of the bone tracts in the femoral neck does away altogether with the theory of the trajectorial structures of cancellous tissue.* Trajectorial structure implies *constancy* of angles of crossing. (TRIEPEL, l.c. p. 2.)

However, there is more evidence since Figs. 3 and 4, sections of Coxæ varæ, show notable atrophy of the elements of the convex side. The distal half of them at the base of the trochanter major is nearly missing altogether. Only, across the femoral head and along the upper border of its neck, directed to the digital fossa, part of it has been preserved and is even strongly developed in Fig. 4. From the *partial* disappearance of the tracts of the convex side, it becomes evident that they must not be considered as a *unit*. For the rest, these bones (of Figs. 3 and 4) are firmly built. This is shown in Fig. 3 by the size of the cortex of the diaphysis, and in Fig. 4 by the strong cancellous tissue in the head and the medial part of the neck. Hence it is certain that these bones have served to bear the body weight. In doing so—*i.e.*, during this static weight bearing—the elements of the *convex* side have *ceteris paribus* had to resist *more tension* and the ones of the *concave more pressure* than normally; for the angle between the axis of the neck and of the diaphysis is nearer a right angle, and with this the moment of the bending force. The increase of pressure stresses on the concave side has indeed led to a thickening of the cortex on the concave side (compare it with the normal cortex in Fig. 1). The *tension* stresses, however, though enhanced, have failed to produce a stronger development of its elements on the convex side. We observe the reverse, viz., *a lessening of the width of the elements of the convex side* in these Coxæ varæ. Instead of a similarity in the reaction of bone to pressure and to tension, we here meet with a *contrast: on increase of pressure a thickening of the bone elements, on increase of tension a thinning away of the same elements*. A parallelism between *tension* stresses and the width of bone elements is not to be seen, whilst between *pressure* stresses and the width of bone elements a parallelism is met with here as elsewhere. The pressure stresses have indeed decreased on the convex side: the pressure stresses which M. gluteus minimus and medius can produce in (the convex side of) the femoral neck and shaft become smaller as the angle between neck and shaft becomes smaller; at a certain degree of Coxa vara they are reduced to naught and pass over into mere tension stresses on farther bending of the femoral neck. With this decrease of pressure on the convex side the thinning away of the tracts of this side is seen to run parallel notwithstanding the increase of tension. In short, *the width of the elements of the concave and convex sides in the various femoral necks shows a parallelism with the degree of* PRESSURE *stresses, whereas between the degree of* TENSION *stresses and the width of bone* *elements any parallelism is wanting*. In the following pages this will appear to be a rule, an exception to which we vainly sought in all other bones in the human body.

We observe that the trochanter major, on the upper and outer part of which the forces of the gluteus medius and minimus act, is atrophic and enlarged in an upward direction—a characteristic, well-known, and annoyingly progressive phenomenon in Coxa vara. So in the trochanter major of Coxa vara we find besides the thinning out of bone tracts on decrease of pressures, also a *lengthening* or "*distension*" on simultaneous pull.

That this phenomenon in bone tissue of *lengthening to pull* (on decrease of pressure) may also occur in bony parts other than the trochanter major becomes evident in the course of this treatise. We shall find in it the ground for a vicious circle, developing on decrease of the pressure stresses, and increase of tension stresses in the convex side of the femoral neck, *i.e.*, for the progressive course by which Coxa vara is characterised as soon as it exceeds a certain degree.

Hence, we find the bone elements thinned out in the enlarged trochanter major (see Figs. 2, 3, 4 and 5), and in Coxa vara also the distal part of the tracts of the convex side, whilst the upper part of these tracts of the convex side—from the digital fossa along the upper border of the neck and across the head—are maintained. The fact that this part answers to the place and direction in which the obturator muscles, pyriformis and gemelli cause pressure stresses in the femoral neck, is not without significance, and is a further ground to dispute the right of ascribing the elements of the convex side of the femoral neck to tension stresses.

So in the convex side of Coxa vara we observe a decrease of cancellous elements where a decrease of pressure stresses exists. The *tension* stresses cause in it no *thickening* of bone elements, not even where they surpass normal intensity; but *they do admit of a thinning out of the bone elements* and they lead to *a lengthening of the* (thinned out) *bone tissue of the trochanter.* Hence, the study of Coxa vara furnishes evidence against the assumption that tension stresses promote bone formation. It even leads to the supposition that pressure stresses are necessary to maintain the bone tissue of the upper femoral end and also to keep it fit to resist tension stresses.

The observations described above concern deformed bones. The difference in their reaction to tension and to pressure might therefore be considered due to some disease of the bone tissue. In the following pages, however, we shall meet with the same phenomenon in normal bones. In other words, *in normal bones* we shall meet with the *same contrast* in the reaction of bone to *pressure* and to *tension*. In fact, we shall find the contrast to be a rule to which we shall in vain search for an exception.

Summing up, elements of the convex side of the femoral neck must NOT *be considered to coincide with the direction of maximal tension, because they often cross the elements of the concave side under oblique angles.* This holds good for normal bones (Fig. 1) as well as for deformed bones (Figs. 2—5). The tracts of the convex side of the femoral neck must *not even* be considered *as tension elements,* because (1) in the living body they also serve to withstand *pressure stresses,* viz., from the short pelvo-femoral muscles, and (2) on an *increase* of the *tension* stresses a *thinning out* of these elements is observed.

The careful study of a number of femoral necks thus reverses all grounds for the CULMANN-MEYER'S crane hypothesis, *i.e.*, for the starting point of the conception of the trajectorial structure of cancellous tissue of bone, and more generally for the assumption that tension stresses have a nutritive effect on bone tissue.

2.—THE CALCANEUM.

A second bone in which tension elements were considered to be traceable, is the calcaneum. Ever since H. MEYER, its structure is generally compared to a pair of folding stairs. Two tracts, starting from the upper joint surface, apparently bear pressure, whilst the third tract, connecting the lower ends of the former two is considered to resist tension.[1] This "tension" tract is visible in Fig. 6, a section of the skeleton of a foot through the axis of the third metatarsal bone. In it a small portion of the cuboid is just visible, which has been cleft in its most medial part. If we compare with it Fig. 7, a section through the second metatarsal bone, and Fig. 8, a section through the first metatarsal of the same foot, the "tension" tract appears to become thinner from the lateral to the medial side of the calcaneum and finally to disappear altogether except for the cortex (see Fig. 8). In other words, the "tension" tract is chiefly—if not exclusively—present where the cuboid is pressed against the calcaneum by the forces which act on the fourth and fifth metatarsal bones and the corresponding toes in a proximal direction, *i.e.*, the part in which the short and long extensors and flexors of the toes with the flexor accessorius and the peroneus brevis and tertius, cause pressure stresses in the cuboid and calcaneum, both while standing and walking. Medial to it where these pressure stresses run higher, along the cuneiform and the navicular bones to the astragalus, rather than to the calcaneum, the "tension" tract decreases. Its development apparently shows a *parallelism* with the intensity of the *pressure* stresses brought about by the muscle action in the bones of the metatarsal and tarsal part of the foot. And it will not do to deny to these pressure stresses, *the action of which is beyond doubt*, a share in the formation of the aforesaid elements and to consider the "tension" tract merely as a product of tension stresses which may possibly run through the concave part of the arch of the foot, but whose presence is still to be proved. Even if it may be assumed that the basal part of the calcaneum in its longitudinal direction is normally subjected to tension stresses—as may be considered probable in abnormal cases, viz., in cases of insufficiency of the muscles (*i.e.*, in flat feet) from the distension and painfulness of the tarso-metatarsal ligament—even then it would not be proved that these tension stresses have a share in the formation of the antero-posterior elements in the basis calcanei, because to the pressure stresses which are acting in the same area, a trophic effect cannot be denied. With regard to the calcaneum as well as to the femoral neck and the other bones MEYER has made the mistake of considering only the static stresses produced by the body weight, and has left out of consideration the dynamic stresses (evoked by muscle action)—a mistake to which ZSCHOKKE (l.c.) has first directed attention. *The very fact that normally the convex side of the femoral neck and the basal part of the calcaneum are exposed to* PRESSURE *from muscle action is the reason why we are not justified in considering those parts as being the result of* TENSION. The basal elements of the calcaneum as well as the tracts of the convex side of the femoral neck have unjustly been cited to support the assumption that tension has the power of bone formation.

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[1] H. MEYER l.c. p. 620.

3.—THE TRANSVERSE ELEMENTS OF CANCELLOUS TISSUE.

Besides the two systems dealt with in the above, MEYER and his followers have simply considered as tension elements all other elements which are at right angles to elements of pressure, and have called them "tension elements." So, for

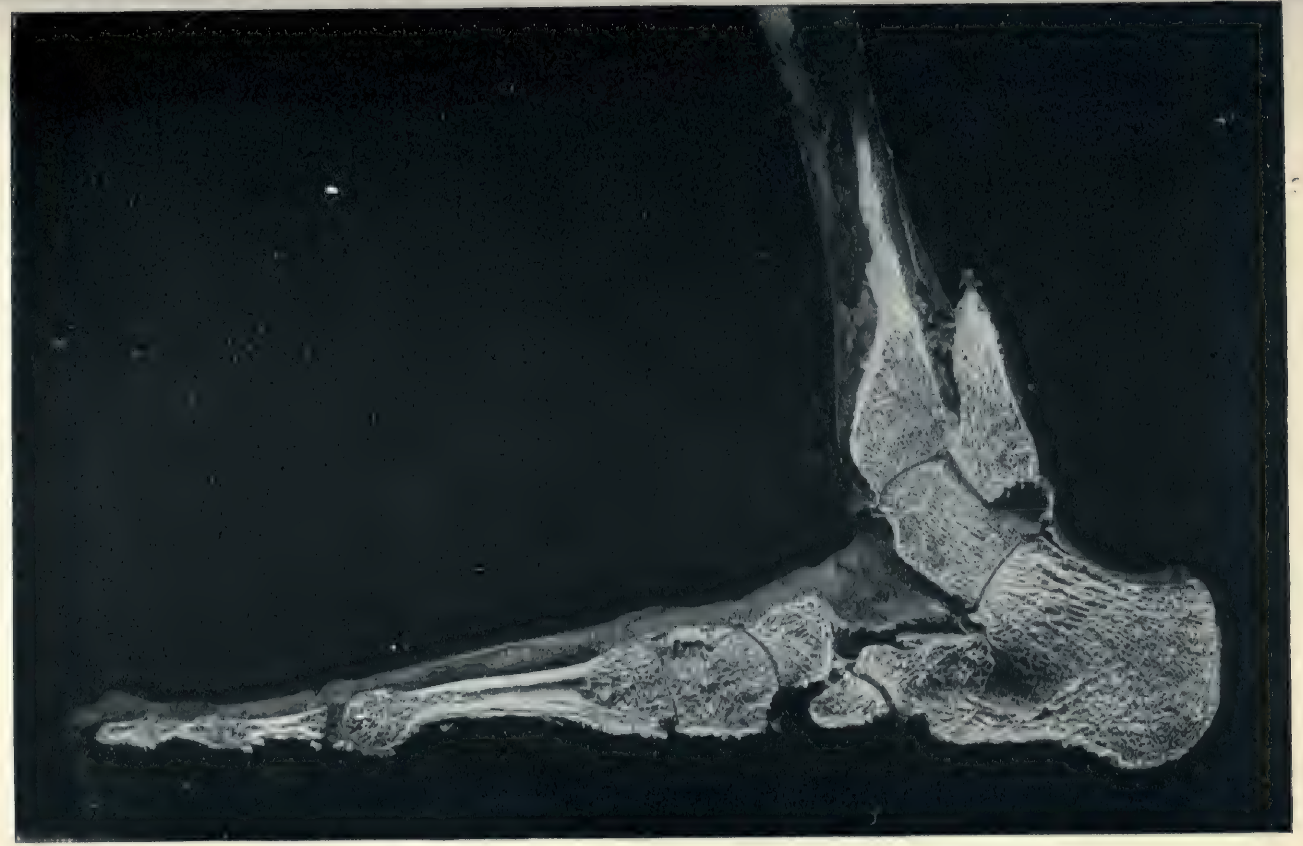
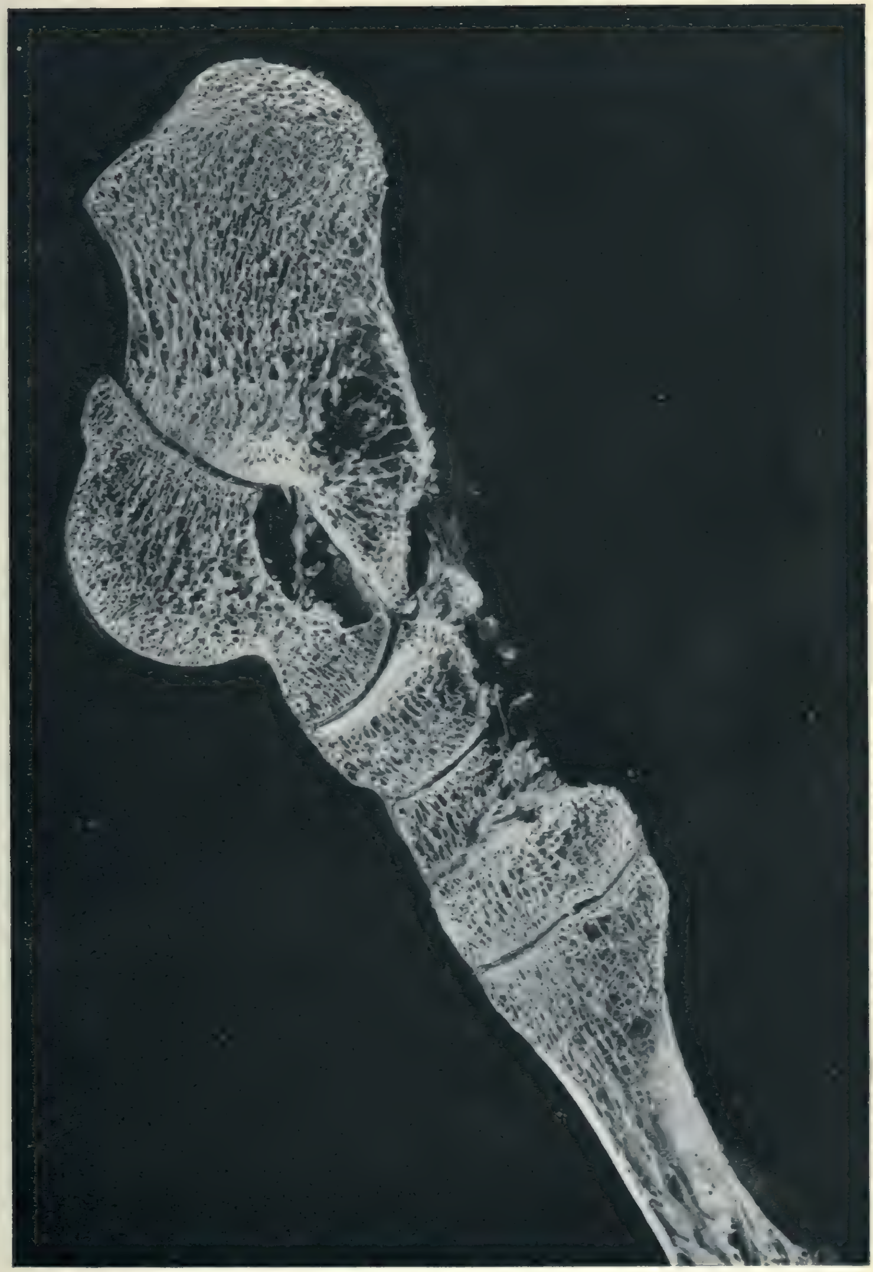


Fig. 6



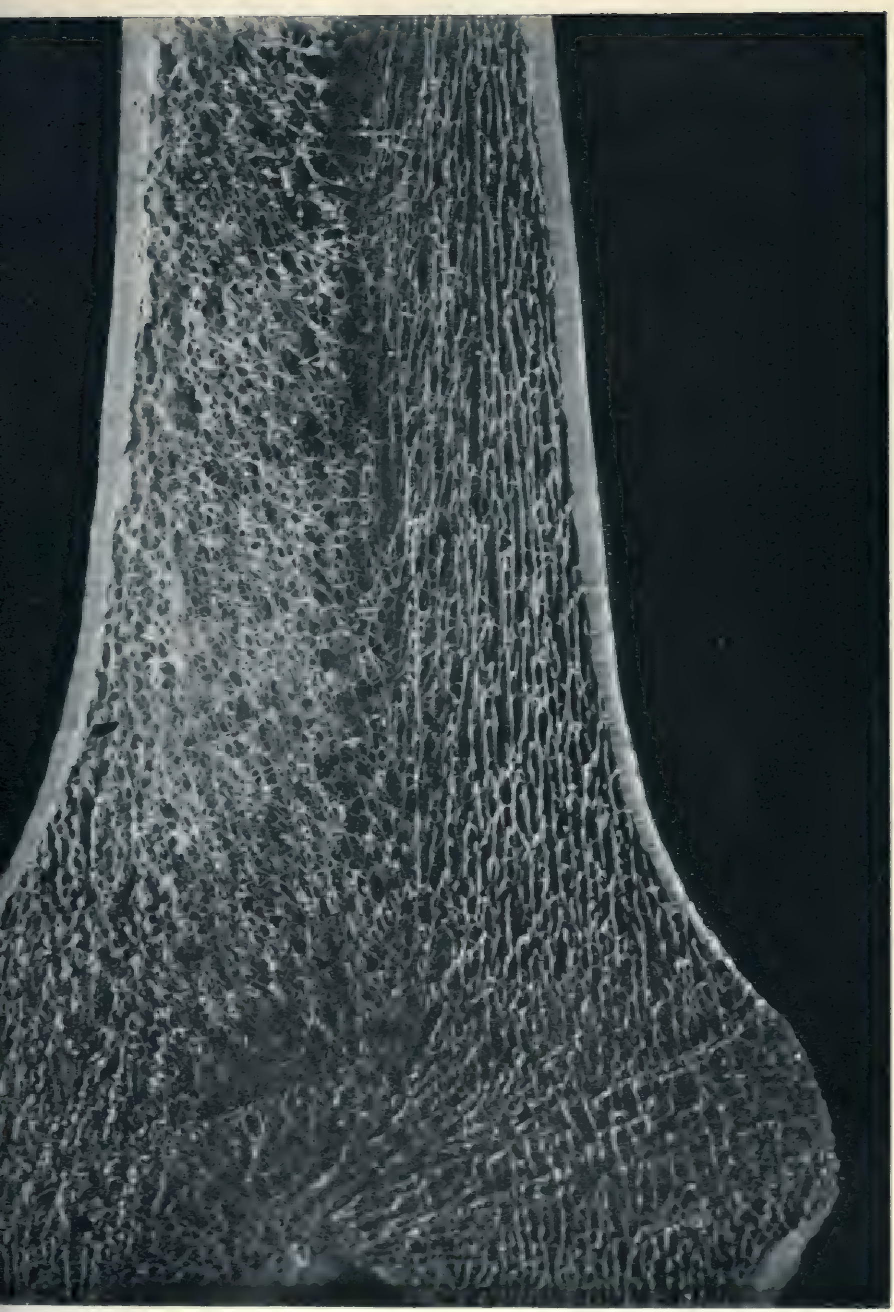


Fig. 9

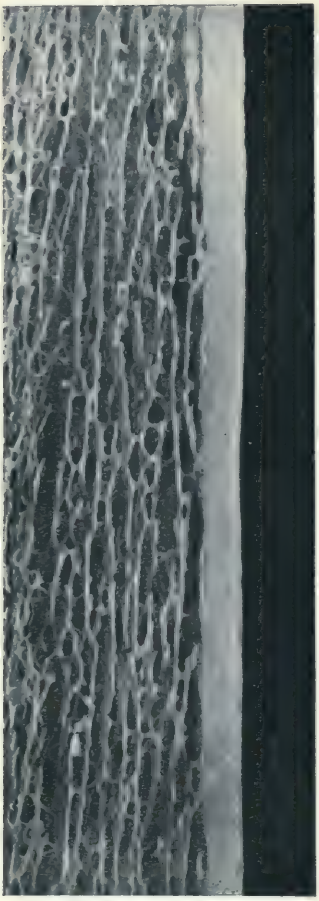


Fig. 10

instance, the bone elements running parallel to the joint surface in the lower end of the tibia (see Figs. 7 and 44), in the bases of the metatarsal bones, the cuneiform and the navicular bones (see Figs. 6, 7, 8 and 48), the upper end of the tibia (see Figs. 41 and 42), the patella (Fig. 45), and the lower end of the femur (see Figs. 9 and 10).

The thesis, according to which in elastic bodies the directions of greatest tension are always at right angles to those of greatest pressure, was simply reversed by MEYER when he stated: the elements of cancellous tissue which are at right angles to those of pressure, viz., the pressure of the body weight, are tension elements. And the transverse elements which did not cross the pressure elements at right angles, were added implicitly to those that did cross at right angles. It cannot have escaped an accurate investigator like MEYER that a number of those transverse elements cross the others at oblique angles. A mere glance at the enlarged photographs of cancellous tissue of the lower femoral end (Figs. 9 and 10), and at the illustrations of the patella (not enlarged) of Fig. 45, may make this evident. MEYER himself indeed correctly represents these crossings at oblique angles in various of his diagrams. These obliquely running elements cannot be assumed to coincide with the direction of maximal tension.

So for these structures the trajectorial conception appears to be untenable. The variation in size of the angles at which the bone elements cross, excludes the very thought of a trajectorial structure. Here the argument can only have been: in elastic bodies pressure and tension stresses cross, here a crossing of elements is found, hence these elements correspond with pressure and tension. But even *this* reversed thesis is untenable because *the transverse elements doubtlessly serve also for conducting pressure stresses.* When in a system of bone tracts, as represented in

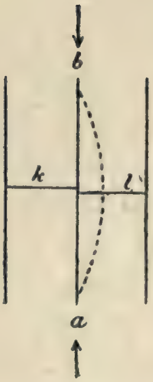


Fig. 11.

Fig. 11, a tract *ab* bends to the right on weight bearing, all transverse tracts in the space *k* will indeed be distended, *i.e.*, they will have to withstand tension, but those in *l* are compressed. Hence in purely rectilinear, mathematically constructed cancellous tissue a weight, acting in a direction which exactly coincides with the direction *ab* of the bone elements, the transverse tracts would have to bear tension as often as pressure. The vertical tracts, however, never follow a purely rectilinear but rather an irregularly undulating course. Now, it is evident that in the case of an undulating course of the vertical elements (see Fig. 12) the ± horizontal bars *n* which unite convex parts of the vertical elements, will sooner have to bear pressure than tension. Before assuming that the transverse elements of cancellous tissue are tension elements, Meyer and his followers ought to have shown that these transverse elements will occur chiefly in places corresponding with those of the bars *m*, where concave parts of the vertical elements face each other. This, however, has not been done. Hence, *no proof whatever has been brought forward to show that the transverse elements of cancellous tissue are caused by tension.*

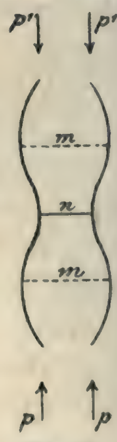


Fig. 12.

If we examine the enlargements of Figs. 9 and 10 in order to ascertain whether the position of the transverse elements agrees with that of *m* in Fig. 12, it appears that the irregularity of the undulations of the vertical elements renders it difficult to state for each separate transverse bar whether the static pressure of the body weight would make it bear pressure or tension. This is all the more difficult, because the vertical elements, which in a certain part of their section curve convexly to the right, are often bent to the left in a somewhat deeper plane. However, there is no doubt that *a large number of the transverse elements unite with the vertical elements on the very spots where convex parts face each other, i.e.*, where weight bearing would shorten their mutual distance and *so* the transverse bars would meet *pressure. A number of these transverse bars moreover cross the vertical elements at oblique angles.* And from this *it may be evident that the transverse elements of cancellous tissues have unjustly and on insufficient grounds passed as elements of tension,* and a fortiori as elements of greatest tension, *i.e.*, as products of tension stresses and of maximal tension stresses. *They certainly serve partly, probably all, to bear pressure.*

4.—THE BONY ANKYLOSED KNEE JOINT.

If we have in the above realised the untenability of the grounds on which CULMANN, MEYER and WOLFF ascribed to tension stresses a trophic stimulus on bone tissue, we are now bound to trace the facts by which ROUX is believed to give further confirmation of this conception. They are derived from a bony ankylosed knee joint, represented in Fig. 13. ROUX states to have carefully removed its cortex so that the superficial layers of cancellous tissue are—partly (author)—visible. We derive this picture from JULIUS WOLFF'S "Gesetz der Transformation der Knochen" (Law of the Transformation of Bones). In ROUX'S treatise itself on the subject[1] it is not given. There we find only the schematic diagram represented in Fig. 14, of which ROUX states that it shows "the same characteristics of the bending construction (Biegungsconstruction)" as Fig. 15—which, like Fig. 14, has been derived from ROUX'S treatise by photography. Comparison of Fig. 14 with Fig. 15 however, shows at once a *difference* between the bending construction of Fig. 15 on the one hand and the course of the bone tracts of Fig. 14 (and 13) on the other. In the schematic figure 15 indeed we see the lines which *start* from the concave side *all curve back to the concave side.* They are the lines which represent the directions of maximal tension, such as are brought about by a bending pressure in the direction of the arrows. The lines of maximal pressure all start from the convex side, and all run through until they reach it again. In Fig. 14 (and 13), however, we nowhere notice tracts starting from the concave side and returning to it. Nor do we observe tracts which start from the convex side and end at the same side. We almost feel sorry that ROUX did not remove the cortex of Fig. 13 (and 14) a little farther, in order that it might have been stated whether the bone elements of the ankylosed knee do indeed return to the same side from which they start. ROUX however, left the cortex of the ankylosed joint on the very spot where facts had to give evidence of the correctness of CULMANN-MEYER'S hypothesis applied to the trajectorial structure of the ankylosed knee. ROUX permitted his imagination to supersede the facts (compare his ankylosed knee (Fig. 14) with his scheme (Fig. 15), led—and as we saw (cf. pp. 12 and 13) misled—by the assumption of the correctness of this hypothesis. And the chance that this imagination, this unproven opinion, should be adopted in science as an established fact, was enhanced, because the picture of the ankylosed knee itself is not given in ROUX'S treatise. Two sections which ROUX made longitudinally through the ankylosed knee differ as essentially from the added schemata. We must abstain from representing them all and refer the interested reader to JULIUS WOLFF, l.c. Tafel viii., Fig. 51, 53, 54 and 55, and page 53.

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[1] W. ROUX, Archiv. f. Anatomie u. Entwicklungsgeschichte. 1885. Blz. 120 ff. l.c.

Here is not the place to trace the reasons for these differences between the facts and their representation.

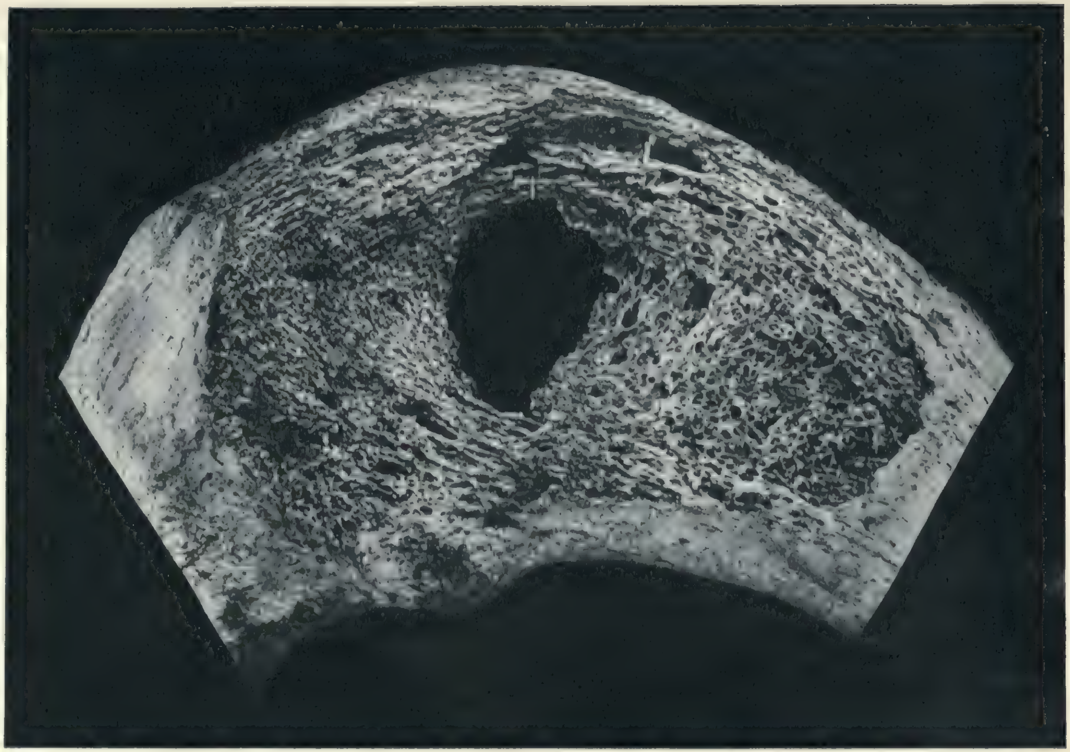

Fig. 13

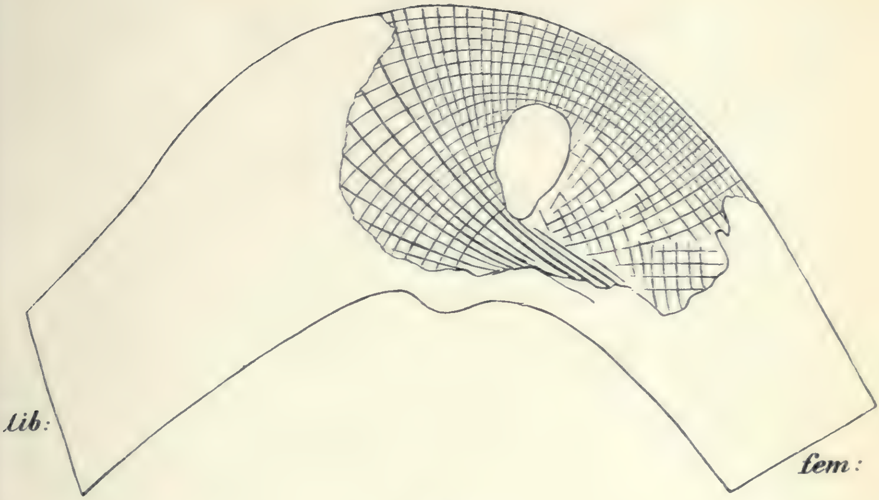

Fig 14

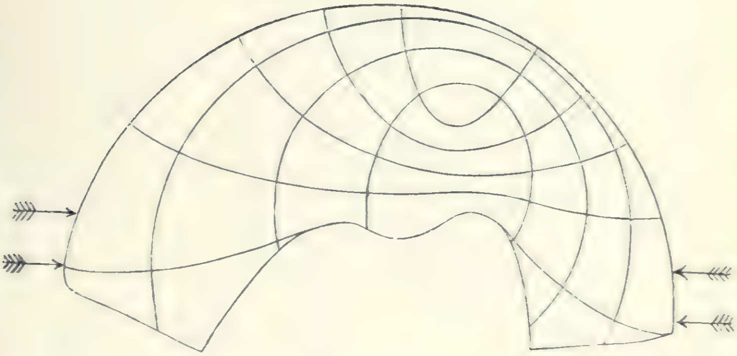

Fig. 15

Nevertheless, they may act as a warning example.

Before communicating the result of our own research, we may establish that *on account of the* ABSENCE *in* ROUX'S *ankylosed knee* (*Fig.* 13) *of the characteristic* TENSION *elements which run uninterruptedly in his* MODEL (*Fig.* 15) *from the concave side along the convex and further back again to the concave side,* the ground is failing to identify the structure of that knee with the tracts of his model, *i.e., to ascribe to tension stresses the bone elements running along the convex side of Fig.* 13.

In the following pages it will become evident that on tracts of the convex side the action of pressure stresses cannot be excluded any more than on the ones along the concave side. In none of the ankylosed knees which we examined, did we find the "tension" elements of ROUX'S scheme (Fig. 15). See Figs. 16, 17 and 18, all derived from one ankylosed knee. In Figs. 16 and 17 a curved system is indeed visible. However, it runs only from the upper end of the tibia to the lower end of the femur in a postero-anterior direction: In the femur it ceases anteriorly, so that it forms about half of a "tension" element in ROUX'S scheme. *The other half,* which—according to this scheme—would have to present itself in the femur and proceed from the anterior aspect upwards to the posterior, *is absent.* And the very absence of this half deprives us of the right to identify this system with that brought by tension in ROUX'S model.

To this must be added that there are also *pressure* stresses passing through the *front* part of an ankylosed knee, even if it is fixed in a flexed position:

(1) In an ankylosed knee the *M. rectus femoris,* being a polyarticular muscle, is maintained[1] in a relatively

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[1] In ankylosed joints polyarticular muscles keep in a relatively good condition, whilst the monarticular muscles atrophy. Cf. MURK JANSEN, Die polyarticulären Muskeln als Ursache der arthrogenen Contracturen. Archiv. f. klinische Chirurgie Bd. 96, 3.

good condition even after atrophy of the three other heads of the M. Quadriceps extensor. And the possibility cannot be denied that the small *extension movements* which are possible through the presence of the remains of the joint line at the fore and the back aspect of Fig. 17 may have led to the formation of the curved tracts mentioned above.

(2) As long as the angle of flexion is small, *standing with the trunk bent forward* will cause pressure stresses at the front part of the knee joint. In that position indeed a normal individual may easily ascertain that within a certain degree of flexion the two patellæ remain quite freely movable laterally, that in other words the extensors remain slack, which proves that *the line of gravity passes in front of the transverse axis of the joint.* So in the knee, ankylosed in the same position, the pressure stresses pass through the same parts of the united femur and tibia.

(3) When the knee is ankylosed in considerable flexion, *i.e.*, when femur and tibia are connected at an acute angle, so that the foot cannot reach the ground, the weight of the leg as such sends pressure stresses through the front aspect of the ankylosed joint. When a support is used fastened to the knee, the same thing happens whenever it is raised from the ground.

(4) Every pressure, acting on the ankylosed knee joint, as by the body weight, and causing tension in its front part, when suddenly removed (as may happen while walking) may be followed by *vibrating movements* during which the tension stresses in the front part of the knee alternate periodically with pressure stresses.

It must be observed that the vibrating movements just mentioned, will be of an importance proportionate to the weight of the vibrating part. This may be the reason why in Coxa vara, the proximal part of which—femoral neck and head—is light and movable in its socket with

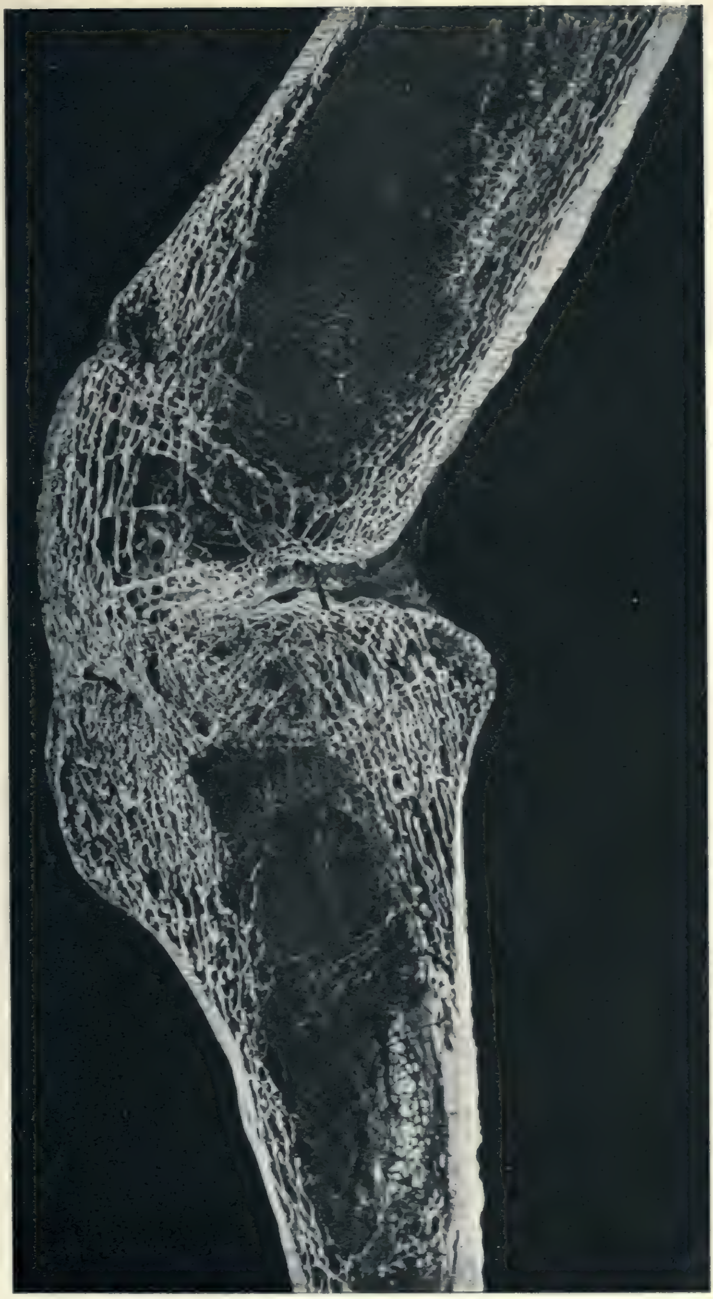

Fig. 16

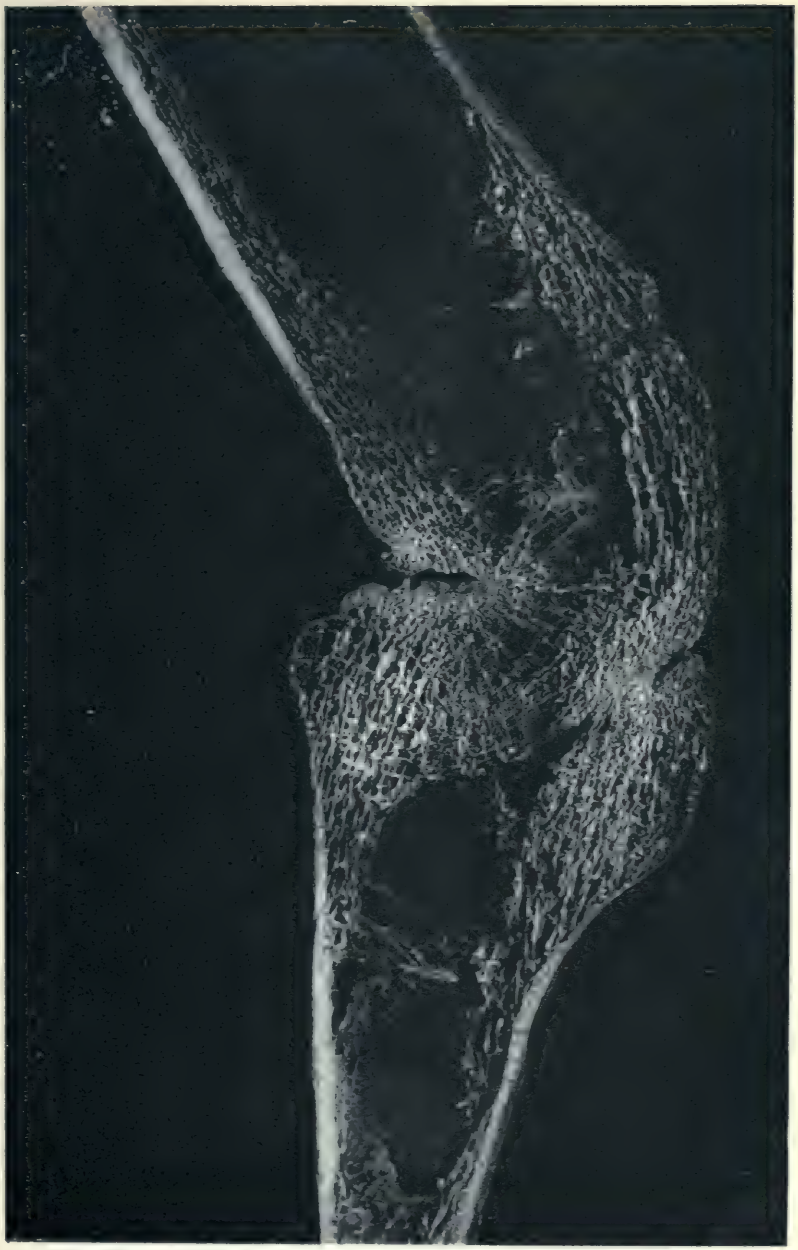

Fig. 17

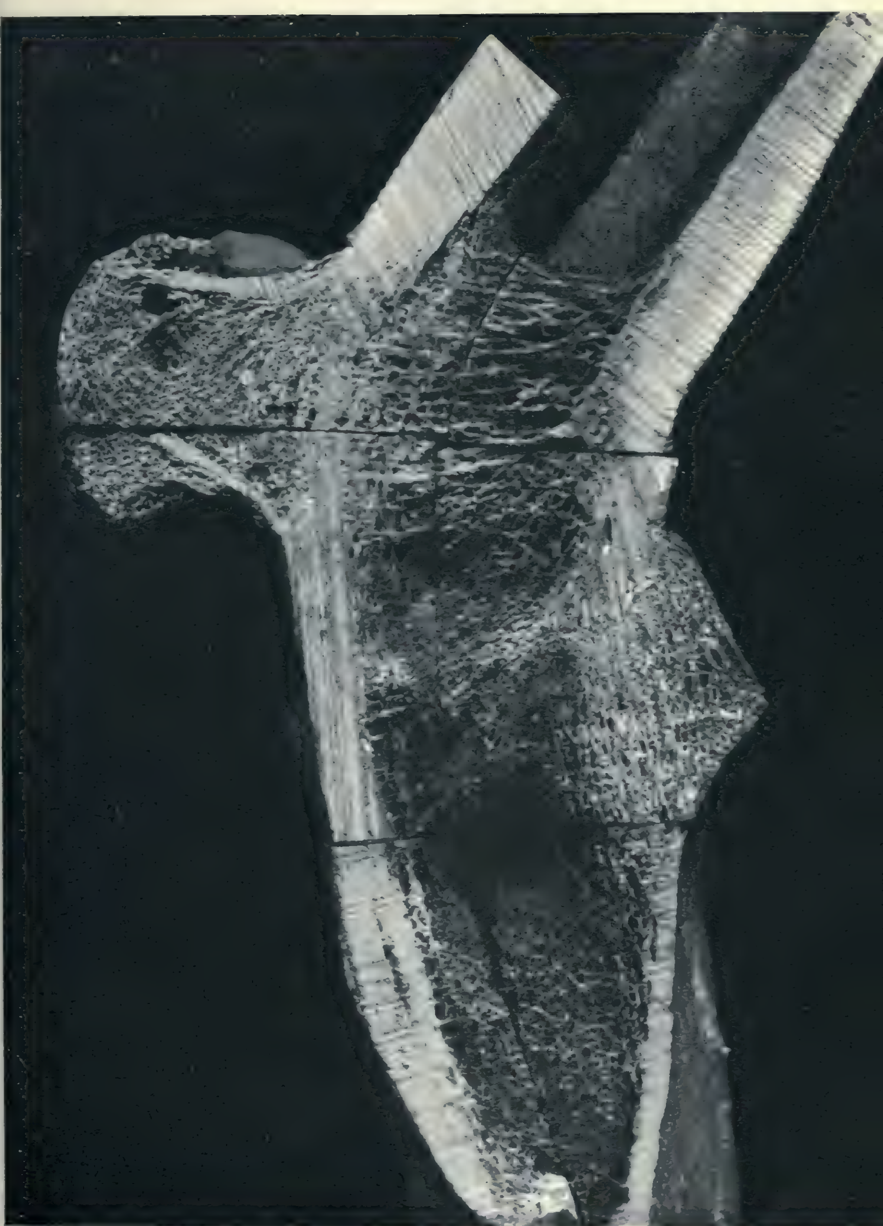

Fig. 19

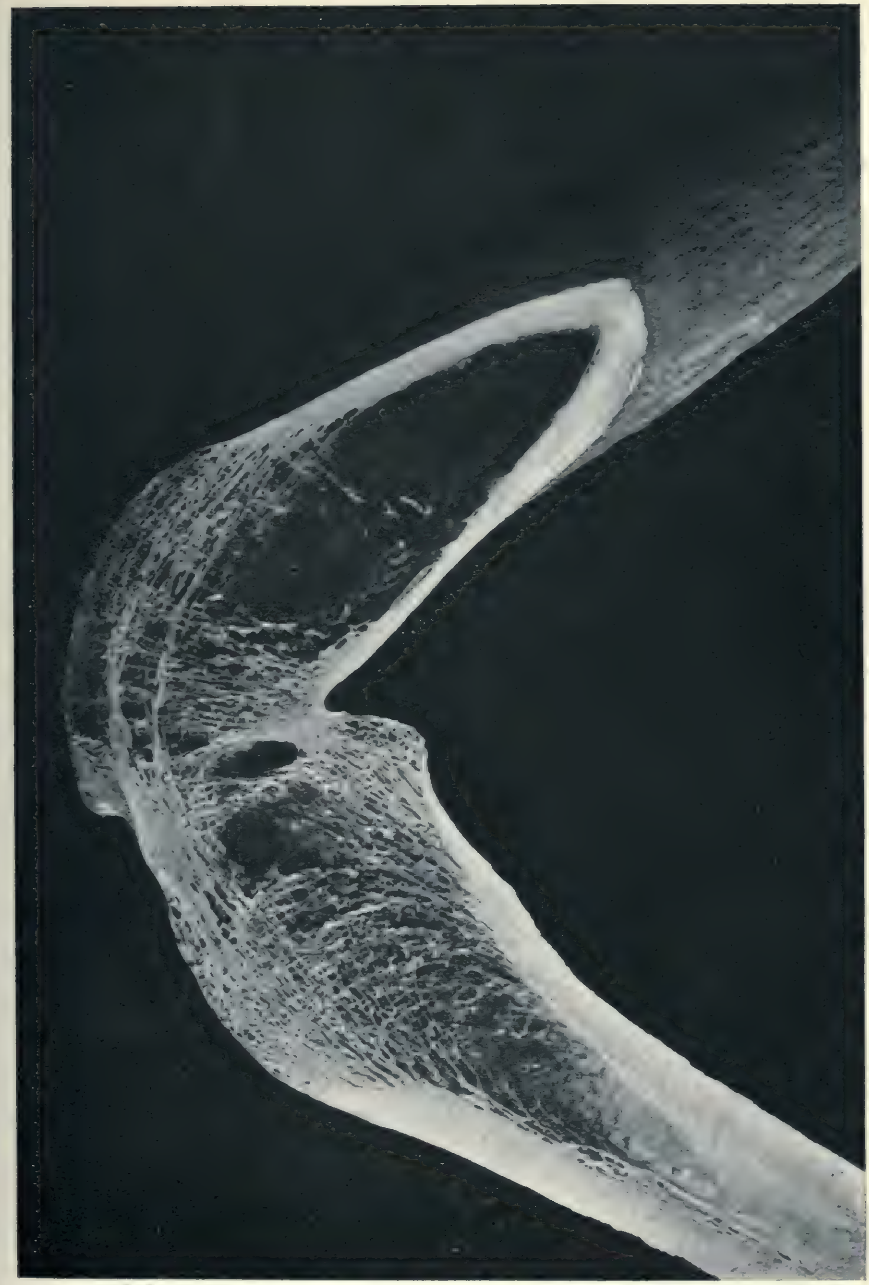

Fig. 20

extremely slight friction, does not at all show the effect of this vibrating movement in its convex side.

Be this as it may, *the very fact that* PRESSURE *stresses also pass through the convex side of the ankylosed knee joint prevents us from considering the tracts of the convex side of these joints as the products of* TENSION *stresses.* They may have been brought about by these pressure stresses. And this is the reason why ankylosed knee joints are inappropriate material to ascertain whether tension stresses are capable of bone formation.

It must be furthermore considered that in an elastic rod which makes vibrating movements—such as must be considered possible during the function of an ankylosed knee (c.f. sub. 4)—tension and pressure stresses alternate along the same tracts. These tension and pressure stresses—as is well known—cross at right angles. This is what makes it plausible why even when pressure stresses only have the power of forming bone, yet bony structures may eventually be built up of tracts crossing at right angles, and thus are not necessarily distinguishable from constructions brought about both by tension and pressure stresses. So, for instance, the thick cortex at the convex side of Fig. 19 and its diverging tracts in the connected patella may owe its origin to a stretching "movement" brought about in one or more of the ways described sub. 1—4. Likewise the cortex at the concave side with the postero-anterior tracts may have been brought about by pressure evoked by bending forces. And the same holds good for the tracts in Fig. 20 which connect the front part of femur and tibia as well as for those which run antero-posteriorly.

So *on the one hand in the bone tracts of ankylosed knees a whole system of "trajectories" is absent which is present in "flexion constructions," viz.,* tracts which start, as well as end, at the concave side and pass in a curve along the convex side, or reversely. *On the other hand it must b admitted as an established fact that on all the bone tract in ankylosed knees pressure has been acting.*

And these are the reasons why neither the bone tract of the ankylosed knee of ROUX *nor those of the ankylosed knees we examined ourselves, may be adopted as a suppor for the assertion that tension has a formative or even nutritiv effect on bone.*

B. In bones formed in membrane.

I.—THE MANDIBLE.

After the equivalence of tension and pressure to bon tissue had seemingly been established by CULMANN, MEYER WOLFF and ROUX, and thus the trajectorial structure o a number of bones formed in cartilage seemed to hav been unanimously proved, it is only natural that the bone formed in membrane should be considered from the sam point of view. This has been done by Dr. OTTO WALK HOFF[1] in a study of the mandible. In it all bone element in whose direction tension stresses may be imagined t have acted are considered as tension elements withou any proof. So for instance, tracts running through th coronoid process are called "tension" trajectories of th M. temporalis (p. 240 l.c.) Two long bone tracts runnin on to the symphysis from the condyloid process unde the alveolar margin—trajectorium dentale and trajec torium basale—and crossing in the neck, are called trajec torium bifidum, which "in the manner of its weight bearin behaves like the crane of CULMANN, which is well fixed a its base." Every proof for this statement is missin

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[1] Dr. OTTO WALKHOFF. Der Unterkiefer der Anthropomorphen und des Mensche in seiner funktionellen Entwicklung und Gestalt. Wiesbaden, Kreidel 1902. (Selenk Studien zur Entwicklungsgeschichte der Tiere II en III).

Only the opinion—untenable as it appeared to be in the previous chapter—that bones formed in cartilage are trajectorial structures, is the ground for the assumption that tension stresses here determine the direction of the bone tracts. That the bone tracts running from the coronoid process of the mandible may as well have met pressure stresses, is left out of consideration. So, for instance, when the mandible is moved laterally, as in chewing movements, or also when it is pulled upwards by the temporal muscle while the mouth is wide open, as in biting movements. Nor is WALKHOFF aware of the fact that the back (lower) part of the condyloid process receives pressure when the mouth is open, and then possibly transmits the same pressure stresses through the trajectorium dentale that the front (higher) part of the condyle transmits through the trajectorium basale, while the mouth is closed. Do physicists hesitate to express an opinion on the course of stresses in simple elastic bodies. Here every hesitation is missing even with regard to so complicated a body which is exposed to numerous muscular forces and to resistances between the teeth. And all this is based on the doctrine of CULMANN, MEYER, WOLFF and ROUX, which, as we saw, in its turn was based on untenable grounds. It needs no further argument that, *before any value can be attached to* WALKHOFF'S *interpretation of the bone tracts in the mandible, it will first be necessary to* EXCLUDE PRESSURE *stresses in the course of his " tension " trajectories. And next it will have to be proved* that an increase of the " tension " stresses in the direction of the " tension " trajectories is followed by a thickening of these bone elements, a decrease by a thinning out, or a disappearance of them; in short, *that a parallelism exists between tension stresses and bone formation.* In the different bones formed in cartilage which were discussed in the previous chapters, we saw that such a parallelism between tension stresses and bone formatio was missing. And it needs no further argument to se that it must not be adopted for bones formed in membran without any proof whatsoever, as WALKHOFF has done.

Hence in WALKHOFF'S *treatise* on the mandible we se nothing like a proof for the trajectorial structure of th bones formed in membrane, but *merely the faithful applicatio to one of the bones formed in membrane of an untenabl thesis which previously had been raised by others for bone formed in cartilage.*

2.—CRANIUM AND PERIOSTEAL BONE.

The cranium has also been believed to furnish suppor for the assumption that tension stresses have the powe of bone formation. In his " Histomechanik des Skeletts (Histomechanics of the Skeleton) and his " Untersuchungen über das Schädelwachstum " (Research on the growt of the skull), THOMA[1] starts from the idea that the cancellou tissue of the human femur proves the equivalence of tensio and pressure to bone formation.[2] So here — as i WALKHOFF'S case—the faithful assumption of CULMANN MEYER'S hypothesis forms the starting point. Furthermore, THOMA assumes that whilst *pressure* is able to forn bone from fibrous tissues by the way of cartilage only *tension* can form bone directly from fibrous tissue as we as from cartilage, which, it may be observed by the way does not tally with the " equivalence of tension and pressur to bone formation."

Tension stresses brought about in the cranium b intracranial pressure, are considered by THOMA to caus its ossification. Thus ossification of fibrous tissue is b him assumed as being proved on the untenable ground c CULMANN-MEYER'S hypothesis, *i.e.*, without any proof.

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[1] R. THOMA, Virchow's Archiv. 1907. Bd. 188, blz. 354 ff.

[2] Id. blz. 355.

By aid of these principles THOMA explains the fact that the early ossification of the skull shows bone tracts radiating from the tubera parietalia.[1] The intracranial pressure which acts at right angles to the cranium, causes—as THOMA justly observes—tension stresses in the cranium which run parallel to its surface. Now this intracranial *pressure* acting at right angles to the surface, THOMA considers to be too small to form cartilage or bone from the fibrous cranium, however the *tension* stresses (parallel to the cranium) *brought about by the very same intracranial pressure* he considers sufficient to form bone directly from fibrous tissue. In fact THOMA considers only *part* of these tension stresses fit for bone formation. Admitting that they start from a certain point, we must note that they run of course partly in radial directions, and partly in concentric circles. *Now it is only to the radial tension stresses* that THOMA ascribes the power of bone formation, the *concentric tension stresses* he considers to be too small. THOMA assumes these radial tension stresses to start from the tubera-parietalia. Thus the radiating structure of the developing parietal bones is "explained." Even for the reader who feels satisfied with this "explanation," the following questions arise:

If indeed tension stresses evoked by intracranial pressure in the membranous brain case should be the cause of ossification of fibrous tissue, why does the dura mater not ossify also? And if tension stresses stimulate fibrous tissue to bone formation, why do not tendons, aponeuroses, fasciæ, and ligaments ossify as well? Why, for instance, is not the linea alba induced to ossify by the tension stresses which intra-abdominal pressure develops in it?

Apparently closing his eyes to these obvious facts, QUANT also writes "that tension forms the formative stimulus for the ossification"[2] of fibrous tissue. He assumes without any proof that tension stresses in the brain case are brought about by growth of the brain.

He says: Tension causes ossification both of the brain case and of the periosteum of the other bones[3] and by muscle action[4]; in the cranium by the growth of the brain. The cranium develops *altogether passively* under the influence of stresses in the membranous brain case which are due to the growth of the brain.[1]

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[1] R. THOMA, l.c. p. 358.

[2] C. A. J. QUANT, Over tri-bounocephalie benevens eene poging om het ontstaan van het schedeldak uit bindweefsel langs mechanischen weg te verklaren. Diss. Leiden 1916, blz. 52 en 53.

[3] Id. p. 63, 64 l.c.

[4] „ „ 64 l. c.

So besides the hypothesis that tension stresses cause fibrous tissue to ossify, we here meet with a second hypothesis, viz., that both in the skull and in the periosteum these tension stresses are produced by growth.

If this were correct, intracranial pressure would have to be higher in children than in adults, and the periosteum would have to gape on being incised in children but not in adults. Brain pressure, however, is regularly found lower in children than in adults[2] (the pressure of the cerebro-spinal fluid is said to rise from 7mm. Hg. in the first year to 15mm. in the adult[3]), and the gaping of a periosteal incision is observed neither in children nor in the adult. Hence we are not entitled to assume that growth causes distension of the brain case and of the periosteum of the other bones.

If we accept for argument both hypotheses, *i.e.*, (1) that growth causes distension of the brain case and of the periosteum of the other bones, and (2) that this distension causes ossification of the brain case and the periosteum of the other bones, we should have to expect that at the end of the period of growth, *i.e.*, on the cessation of this distension—and with it of " the formative stimulus for ossification " —the brain case and periosteal bone would atrophy or relapse into the condition of fibrous tissue—which is not observed.

If, notwithstanding the above facts, we should assume that growth of the brain caused distension of the skull, even then the assumption that such distension causes ossification of the brain case, is opposed by the fact *that the dura mater, though under the same mechanical conditions, retains its fibrous nature.* And, speaking more generally, to the idea that " tension causes ossification " of fibrous tissue is opposed the fact that in the human body *the various fibrous tissues, though transmitting tension stresses, persist as fibrous tissue* throughout the life-time and have been doing so throughout the generations.[4]

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[1] Id. p, 63 l.c.

[2] Krause, Chirurgie des Gehirns und des Rückenmarks.

[3] Thoma, Untersuchungen über das Schädelwachstum und seine Störungen. Virchow's Archiv Bd. 224, H. I, blz. 79.

[4] Some more objections to Quant's considerations, which like those mentioned above, we brought forward at a meeting of the Medical Society in Leiden, have been here omitted, since they are not pertinent to the present argument.

The origin of the cranium as well as of the products of the branchial arches and other bones will be dealt with in Chapter V., pp. 79 and 80 and Chapter VII., pp. 99 and 100.

Summing up the contents of Chapter II., A and B, it appears that on insufficient grounds *a trophic stimulus to bone tissue has been ascribed to tension stresses.* It has been left out of consideration that upon the elements of the convex side of the upper femoral end, the antero-posterior tracts of the calcaneum, the transverse elements of cancellous tissue and the curved elements of ankylosed knees, pressure stresses have been transmitted which may have caused the formation of these elements. *A parallelism which appears to exist between the width of bone elements and the intensity of the pressure stresses, has never been demonstrated for tension stresses.* CULMANN-MEYER'S hypothesis that tension stresses cause bone formation in the upper femoral end has been simply applied to the other bones formed in cartilage as well as to bones formed in membrane without any proof whatever. Moreover, *from the fact that mechanical forces appeared to have an effect on the formation of bone tissue, a theory has been advanced to consider all bone formation as dependent on mechanical stresses.* Wheresoever pressure stresses were failing or seemed to be insufficient, tension stresses—even though problematical—were assumed (pp. 29 and 30) to have acted as a cause of transition of fibrous tissue into bone. The daily experience that fibrous tissue which is submitted to tension, remains fibrous for a life-time and throughout the generations, has been lost sight of altogether.

The obstinacy with which the doctrine of bone-formation-through-tension has thus taken root in medical literature, can be explained only by the attractiveness of the conception of a trajectorial structure of the bones which gave rise to it. The attractiveness of a notion, however, does not afford a measure for its correctness. Facts will have to give their verdict. In the following chapters some new facts will be brought forward. From them it will become evident that in deformed bones osseous tissue disappears, and in normal bones osseous tissue is absent, wherever only tension stresses are evoked. And thus the evidence of facts will overthrow the dualistic doctrine according to which both pressure and tension lead to bone formation, and cause it to be replaced *by the monistic conception that to pressure only a trophic effect on bone tissue has been assigned.*

CHAPTER III.

TENSION GIVES NO TROPHIC STIMULUS TO CANCELLOUS TISSUE.

A. In deformed bones.

Fig. 21 is the photographic representation of an apex or wedge vertebra of a right dorsal lateral curvature. The figure represents the upper surface. Researches made by ALBERT,[1] RIEDINGER,[2] and others have taught that the line which joins the middle of the arch and the body of such a vertebra, shows a curved course having the convexity directed to the concave side of the lateral curvature, in a way indicated in the figure. Hence the vertebra is bent in the plane of the figure, its mesial plane has become convex to the left half of its body. It is well known that this bending of the vertebra forms part of the phenomena which in the scoliotic spine are collected under the name of "torsion," and which are characterised by the fact that the vertebral bodies deviate more from the middle line than the vertebral arches. What forces bring about these torsion phenomena may be left undiscussed. It may here suffice to state that certain forces—not to be traced here—have bent the dorsal vertebra of Fig. 21 in its mesial plane, so that it may be considered probable that the left half of the vertebral body and arch have striven to get farther away from each other, the right halves on the contrary, tried to approach each other. The pressure which normally acts on the left pedicle in an antero-posterior direction was thus diminished or turned into tension, whereas pressure was enchanced in the right pedicle. We see that the middle of the vertebral body has got farther away from the left transverse process and the articular process at its base than from the right, although this is partly overshadowed by the enlargement of the left half of the vertebral body, to which we referred above. The left vertebral half is in other words lengthened in the plane of the figure as compared with the right half. Fixed by the adjoining vertebral bodies, the wedge-shaped body of this apex vertebra has been pressed to the right, whilst the frontal direction of the articular surfaces of the adjoining vertebral arches above and below, assisted also by ligaments and muscles, prevented the arch from getting displaced in the same direction.

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[1] E. ALBERT, Der Mechanismus der skoliotischen Wirbelsäule.—HOLDER, Wien 1899.

[2] Vgl. W. SCHULTHESS, Joachimsthal's Handbuch. 1 Bd. p. 760.

A vibrating movement such as had to be assumed for the ankylosed knee, in which the pressure acts in intermittent shocks so that parts put under tension stresses have periodically to withstand pressure stresses and reversely, is here—in the vertebra—hampered by that fixation and is surely of little moment on account of the smallness of the vibrating parts.

Be this as it may be, we *see* the pedicle of the right side, which has (in all probability) met harder pressure than normally, thickened, whereas *the one on the enlarged left side is not only thinned out but even shows a gap* ; so that it may be assumed that through this gap no pressure whatsoever can have been transmitted.

It might be argued that in the left pedicle pressure stresses have disappeared without passing over into tension stresses, that the atrophy of this part is the mere result of the absence of any stress whatsoever, be it either pressing or pulling ; that the tension stress would have been

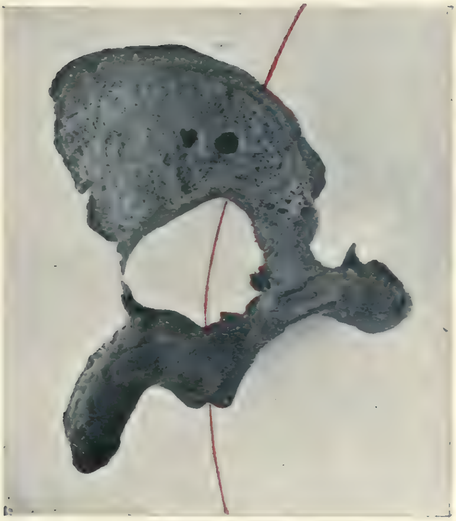

Fig. 21

brought about in the left pedicle only after a somewhat stronger bending of the mesial plane. Those who ascribe to tension stresses a trophic effect on bone, might thus assume that only on such an increased bending of the vertebra the thickening of the pedicle could appear. If this were correct, the apex or wedge vertebra of a dorsal lateral curvature, would now and again show a thickening of the pedicle on the convex side of the vertebra, *i.e.*, on the concave side of the scoliosis. Experience, however, teaches that *the thinning out of the pedicle on the convex side of the apex vertebra* (*i.e.*, on the concave side of the scoliosis) *is a constant phenomenon of dorsal* scoliosis which has been long known. It is less marked in vertebræ which are farther away from the apex of the curvature, so that in multiple scoliosis the lozenge-shaped or oblique vertebrae—*i.e.*, those lying where two opposed curves meet—show about the same width of the two pedicles.

For the pedicles of the lumbar vertebræ the thinning out of the pedicle on the concave side of the curvature—does not hold good.[1] This might be misused as an argument against the meaning of this phenomenon in the dorsal vertebræ. Therefore we must observe that in the lumbar part of the spine the mechanical conditions of the pedicles are different. So for instance the articular surfaces of the vertebral arches show a sagittal—instead of a frontal—direction. And when in the last lumbar vertebra the concave sided pedicle is thicker than normally,[2] it must be borne in mind that this pedicle has an almost vertical direction in the upright spine,[3] quite adapted, in connection with the lordosis in this region, to transmit part of the body weight to the sacrum.[3] It is not our task here to deal fully with the mechanical relations of the pedicles in the various parts of the scoliotic spine. It may suffice to point out that differences in position, between the pedicles in dorsal and lumbar vertebræ, go hand in hand with differences in the mechanical forces to which they are subjected.

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[1] Cf. Joachimsthal's Handbuch, W. SCHULTHESS. S. 668.

[2] Ibid. P. 678 and Fig. 472 a—d.

[3] Ibid. P. 495 and 496.

Not only the phenomenon of *the atrophy of the left pedicle* in Fig. 21 itself, but also *the constancy of this phenomenon on the convex side of each dorsal vertebra, the mesial plane of which is bent, is an argument against the assumption that tension should have a nutritive effect on bone tissue,* at least as far as deformed bones are concerned. The parallelism to the recognition of which we have been forced here, as in other cases, between the width of the bone elements—in casu the width of the pedicles—and the intensity of the *pressure* stresses evoked in them, *is* totally *failing between the intensity of the tension stresses and the width of the bone elements. Instead of a* SIMILARITY *in the effect of pressure and tension* in the bent vertebræ and in the deformed femoral neck (see Fig. 3 and 4)—*in the behaviour of bone tissue we meet with a* CONTRAST *regarding* PRESSURE *and tension*, a contrast which in the following pages we shall find in other deformed as well as normal bones without any exception.

By the way, it may be noted that the enlargement which the vertebral body of Fig. 21 shows in its left part, *i.e.*, in the concave side of the scoliosis, is in no contradiction whatever with the above. In that part the pressure of the body weight has made itself felt in an axial direction. So tension need not be made responsible for it.[1]

In perfect agreement with the separate vertebræ is the behaviour of the spine as a whole, when it is deformed.

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[1] To what extent this enlargement may be part of the original vertebral body and due to internal displacement is a question—not of bone formation but—of bone deformation which cannot be dealt with here.

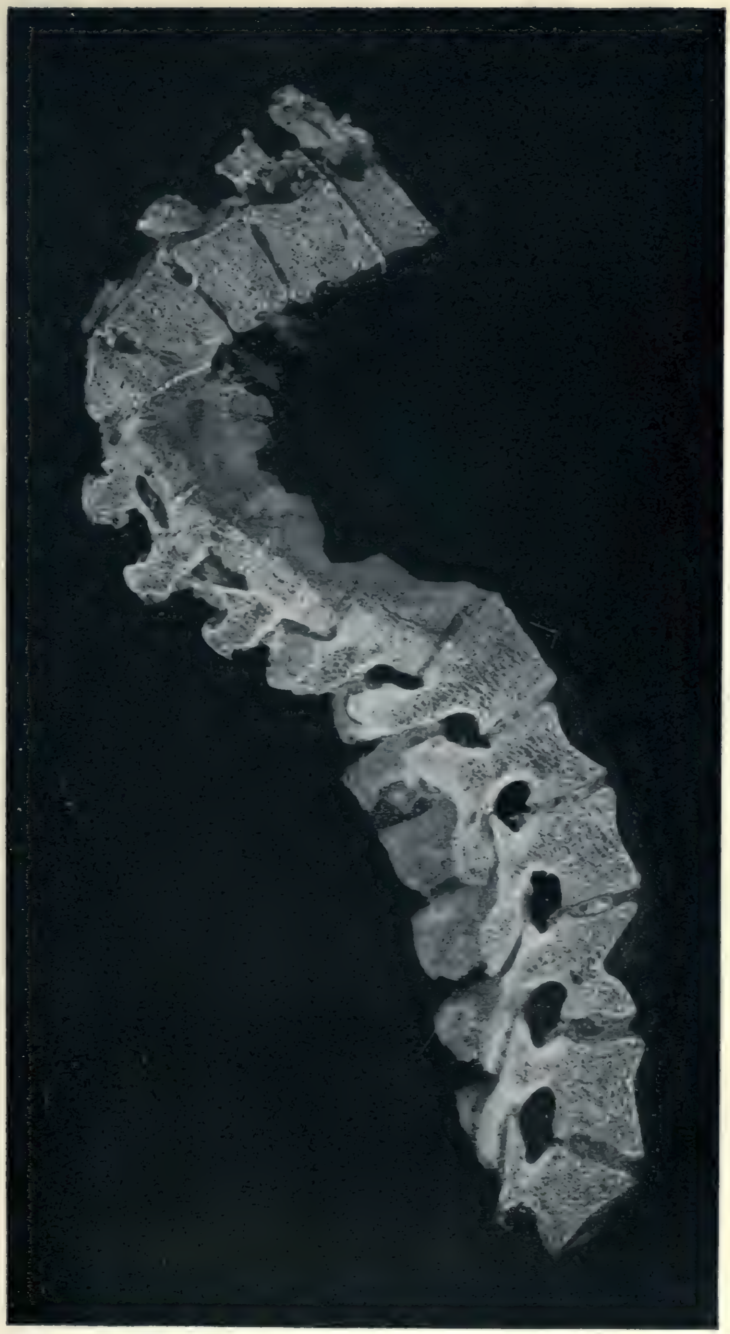

Fig. 22

There, too, we meet with an atrophy and rarefaction of the bone elements, when the bend in the spine is so sharp that we are forced to assume that the normal pressure stresses, at least in the upright attitude, have been converted into tension stresses.

Fig. 22 is a scoliotic spine sawn in such a way as to lay bare in its dorsal curve, as much as possible, symmetrical parts of its cancellous tissue both of the bodies and the transverse processes. For that purpose the sections had to be made in different planes as may be inferred from the shadow on the concave side of the dorsal curve. As this shadow on the figure hampered a comparison of the density of the bone tissue on the concave with that on the convex side, we have photographed the same specimen a second time, turning it before the light together with the photographic apparatus, so that convex and concave sided elements caught the same quantity of light and the shadow was obviated.[1] In this way Fig. 23 was obtained. Observe the density of the cancellous tissue in the articular processes on the concave side of both lateral curvatures. These processes have to a large extent taken over the pressure of the body weight from the vertebral bodies which sinuate along the processes so as to exaggerate the convexity of each curvature. The density of the bone tissue is seen to diminish in a transverse direction from the concave to the convex side of each curve. So here again we observe the well-known parallelism between the intensity of the pressure and the width of the bone elements. *And if on the convex side of the two curvatures the pressure stresses have passed over the neutral point into tension stresses, the latter have failed to cause bone formation.*

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[1] This was done by Dr. J. W. C. Goethart, director of the Herbarium and Lecturer on Botany in Leiden University, who devised this apparatus for the accurate reproduction of ribs and veins of leaves and rendered us great service by using it for the object mentioned above.

The highly atrophic spine of Fig. 24 showed the same characteristic sinuating course of the vertebral bodies with respect to the transverse processes, although it is not visible in the photograph. Here, too, the atrophy on the convex side is noticeable as compared with the condition on the concave side, namely in the upper curve. If it may be assumed that this spine had the same form during life, the downward direction of the upper end renders the action of tension stresses on the convex side —during life also—very probable, at least in the upright attitude. Whether the vertebral bodies lower down in this spine, which form the lower curvature, have undergone enlargement and atrophy under the influence of tension stresses, may be left undecided.

Summing up we see an atrophy and rarefaction of bone elements wheresoever it may be assumed on reliable grounds that during life pressure stresses have diminished or have been replaced by tension stresses. This holds good for the pedicle in the convex side in the apex vertebra of dorsal scoliosis (Fig. 21), and for the convex side of the scoliotic spine as a whole (Figs. 23 and 24), as well as for the elements of the convex side in the femoral neck in Coxa vara (Figs. 3 and 4) which we studied in the first chapter. *A parallelism which we observed constantly between pressure stresses and the width of the bone elements, appears to be failing with regard to tension stresses, at least in deformed bones.*

Totally different from the bent ankylosed knee, in the convex side of which strong bone strips are noted, we see such thickening of bone elements constantly missing in the convex side of scoliotic spines and Coxæ varæ. And this difference may be easily accounted for. The vibrating movement during which tension stresses alternate periodically with pressure stresses, is great in ankylosed knees but small in vertebræ and Coxa vara: the mass of the vertebræ is small as well as that of the femoral

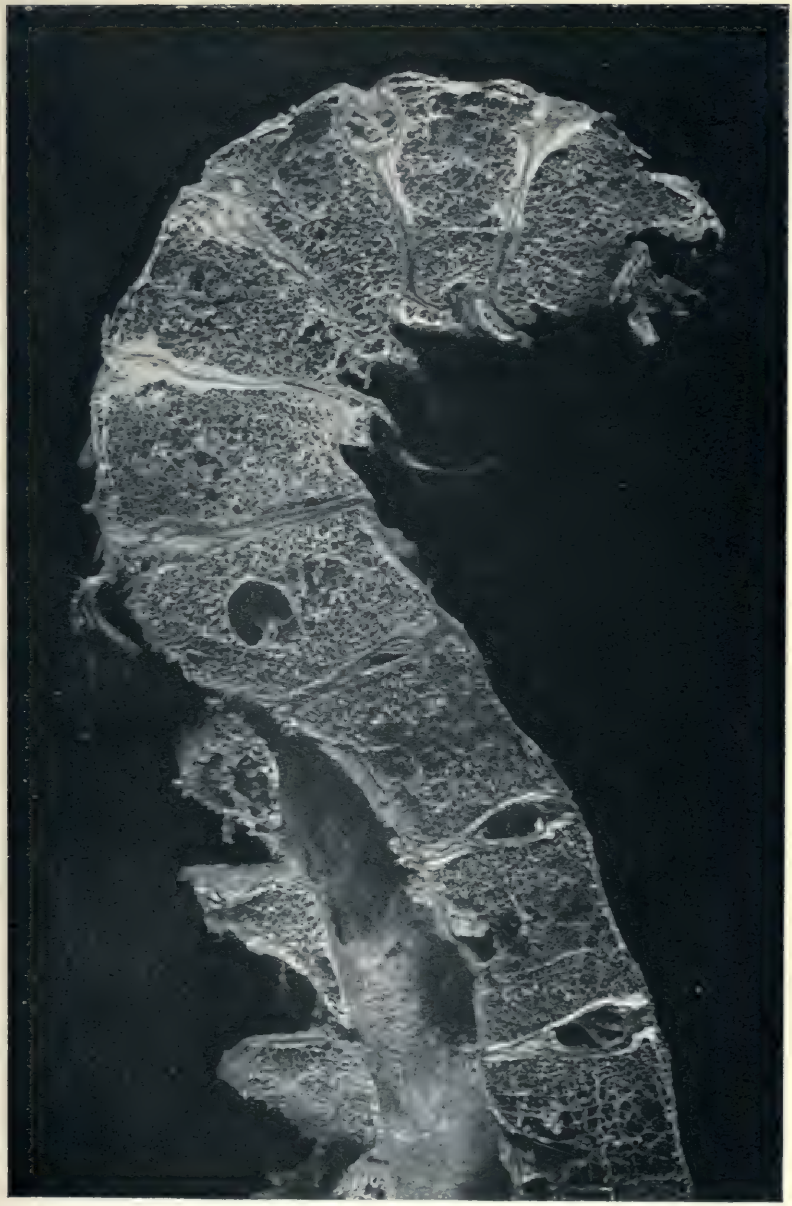


Fig. 24

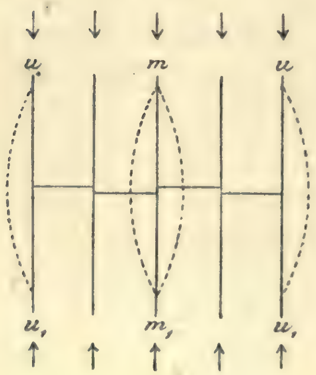
neck, and the intervertebral discs act as a buffer reducing the elastic pressure of the vibrations, even when—as in the case in Figs. 22 and 23—a few of the vertebræ have formed bony union. And it is for this reason that on the one hand the deformed spine and femoral neck are suitable objects for studying the effect of a decrease of pressure stresses or a transition into tension stresses on the convex side of their curve, whilst on the other hand the ankylosed knee seems to be material well adapted to lead the uninitiated investigator astray.

The opinion might be held that the difference in behaviour between ankylosed knees on the one hand and vertebræ of scoliotic spines and Coxæ varæ on the other, could result from a difference in condition of the bone tissue. The deformed spine might indeed be considered as composed of diseased bone "struck by rickets" and the ankylosed knee even after the agents causing the ankylosis have ceased to act, cannot without dispute be considered as normal bone. Therefore in the above we have strictly speaking shown only that in abnormal bones tension stresses are unable to maintain bone tissue. Hence the advantage which bent and deformed bones offer for the study of bone formation in their allowing a comparison with normal structures, is counterbalanced by the fact that what has been thus found with regard to abnormal bones cannot at once be applied to normal bones. In the following pages it will therefore be our task to ascertain whether in normal bones tension stresses are able to cause the development of bone. For that purpose we will compare normal bones in which differences of tension stresses evoked in them during life, give evidence of having produced differences in structure by the parallelism they show with these differences of tension. Normal vertebral bodies will prove to be suitable material for reasons which may become patent in the following chapter.

B. In normal bones.

The cancellous tissue of (normal) vertebral bodies chiefly consists, as is well known, of vertical (axial) elements which run from one end surface to the other and are mutually connected in many places, partly by thin bars running transversely and obliquely, partly also by wider elements (see Fig. 26c). It is obvious that the vertical elements bear the pressure of muscle action and gravity during life, while the transverse and oblique elements connecting them, limit or prevent their bending, as has been dealt with on pp. 19 and 20. This relation is represented schematically by Fig. 25. We observed (cf. Fig. 11) that a central element *mm* (see Fig. 25), which is supported on both sides by cross bars, on weight bearing, will as often bend to the left as to the right and will thus alternately evoke pressure and tension stresses in the transverse elements. The peripheral elements uu_1 on the contrary (Fig. 25), which meet with no resistance on the outer side, will bend oftener outwards, and in so doing evoke tension stresses in the transverse elements which connect them with the elements situated more centrally. So in a vertebral body which is entirely built up according to the scheme of Fig. 25, when being pressed in the direction of the arrows, the vertical elements in the periphery will tend to bend out like the staves of a barrel, causing tension stresses in the transverse elements which connect them with the vertical elements situated more centrally as well as in those which connect them mutually. Hence, if tension stresses have indeed a formative effect on bone, the lateral surface of the vertebral bodies which unites the parallel

Fig. 25.



end surfaces, might have the form of a cylinder mantle, or even bulge so as to make the vertebral body adopt the form of a barrel. In this latter case the transverse elements of the periphery would have to withstand tension only whenever the vertebral body should be made to bear weight.

Therefore if the vertebral bodies were barrel shaped, in the periphery of those bodies a cancellous tissue could be present in the sense of MEYER, WOLFF, ROUX, *and their followers, in which the pressure of muscle action and gravity would cause pressure in one system* (the axial elements) *and tension in the transverse elements* (at right and oblique angles to the axial elements). However, the vertebral bodies never adopt the shape of a barrel. On the contrary their lateral surface regularly shows a concavity. So, pressure on the end surfaces causes the vertical elements in the periphery to tend to bend further inward, *i.e.*, in a central direction, and to transmit pressure to the central parts (see Fig. 26B). When the trunk bends forward, this pressure, which is the result of body weight and muscle action, is directed from the front part of the vertebral bodies to the centre in an antero-posterior direction. In side movements it starts from the lateral aspect of the vertebræ and is also directed to the centre ; in short, in each bending of the spine, pressure is transmitted through the vertebral bodies in a radial direction. That these radial forces from the periphery to the centre of the vertebral bodies do not all run parallel to their end surface needs no argument. It is very probably in connection with these radial forces that their transverse elements show a radial course in the middle of the heights of the vertebral bodies (Fig. 26A) and assume the form of plates (cf. Chapter IV. B) more distinctly there than nearer to the end surfaces, and that the strips of bone which in Fig. 26B diverge from the lateral surfaces of the vertebra to the upper and lower end surfaces, may be considered as results of pressure directed obliquely inward. *So in vertebral bodies the transverse and oblique elements as well as the vertical elements seem to resist pressure and*—as in all other bones we examined—*a parallelism between the development of these elements and the pressure acting upon* them is patent. Around the concave lateral surface of the vertebral body, on the contrary, *i.e.*, where only the vertical elements would have to resist pressure and the transverse ones would be subject to tension, both these transverse and the longitudinal elements are failing, *i.e.*, the bone tissue as such is absent altogether. In other words *where the transverse* (*and oblique*) *elements would miss the trophic stimulus of pressure, it is not only these that prove to be absent, but the vertical elements as well.* The concavity of the lateral surface of vertebral bodies thus raises the thought that cancellous tissue needs pressure stresses for its existence both in its transverse and its vertical elements, because the presence of tension and the absence of pressure in transverse (and oblique) directions appears to coincide not only with absence of the bone elements in those directions but even with absence of the vertical elements, whose firm connection they would have to secure.

The opinion might be held that this idea is not justified because it is drawn from the study of a single vertebra. However, if we compare the lateral surfaces of different vertebræ of the same spine as well as those of the spine of different animals, it appears that *the concavity of the lateral surface of vertebral bodies is deeper in proportion as their mutual mobility is greater.*

Figs. 27—30 successively represent the spine of a rhinoceros, a kaffir buffalo, oreas oreas and antelope, in which by removal of some ribs the anterior outline of the vertebral bodies has been rendered visible against a

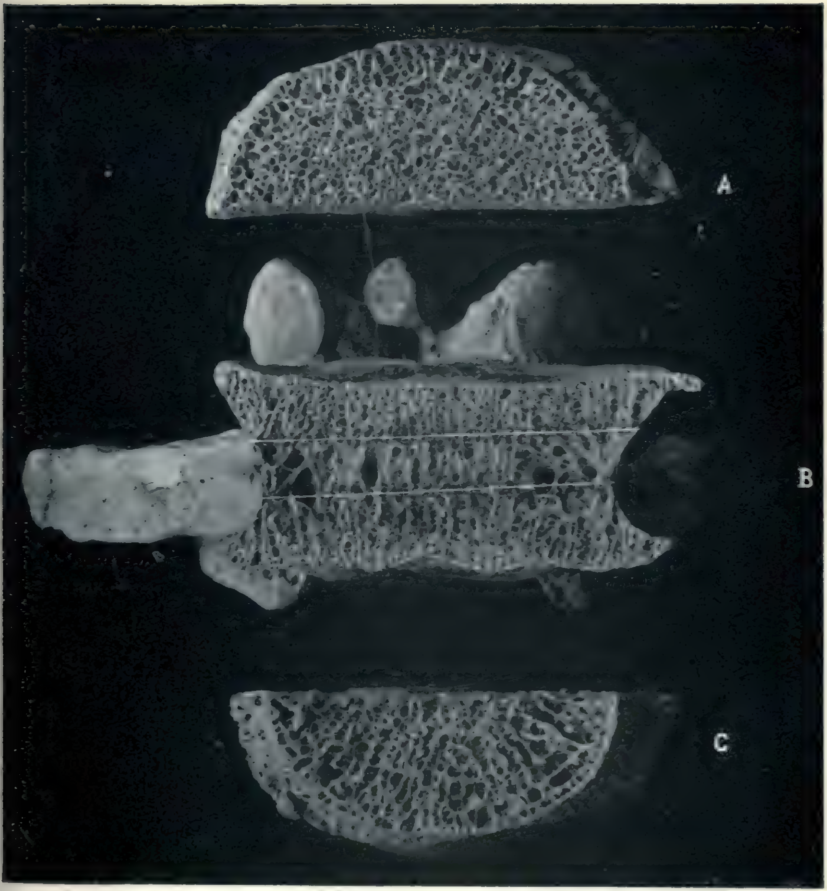


Fig. 26

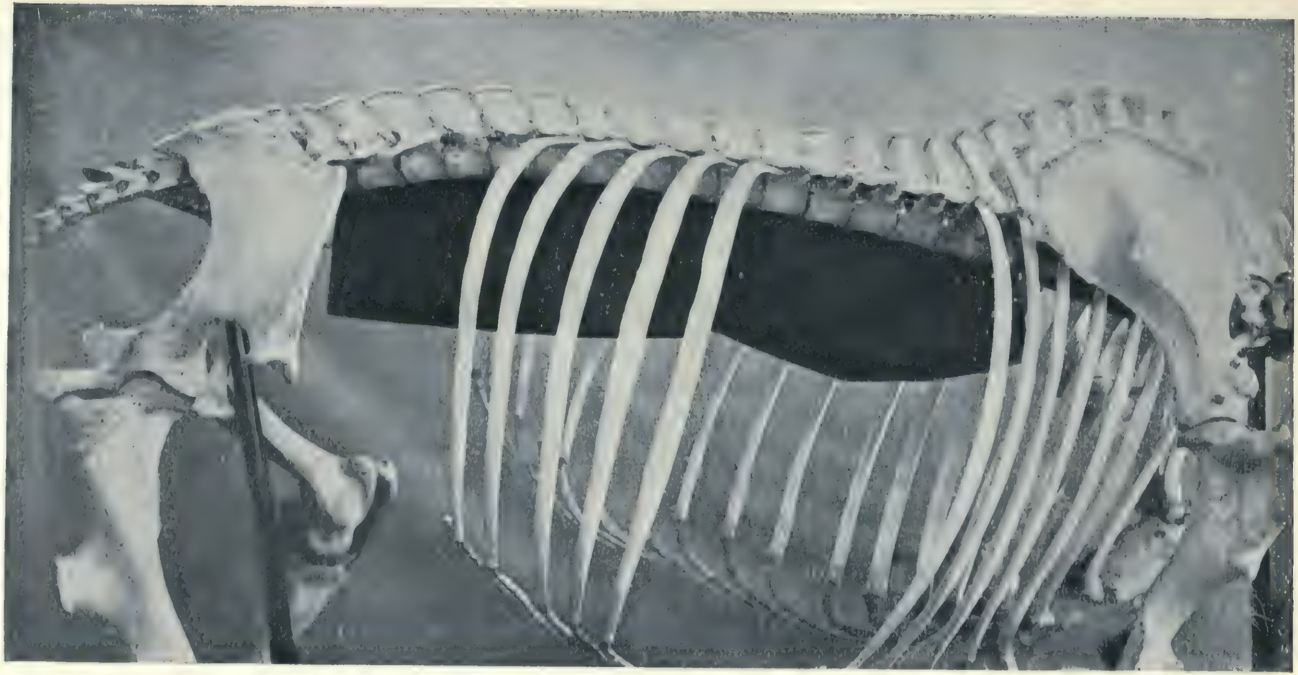


Fig. 27

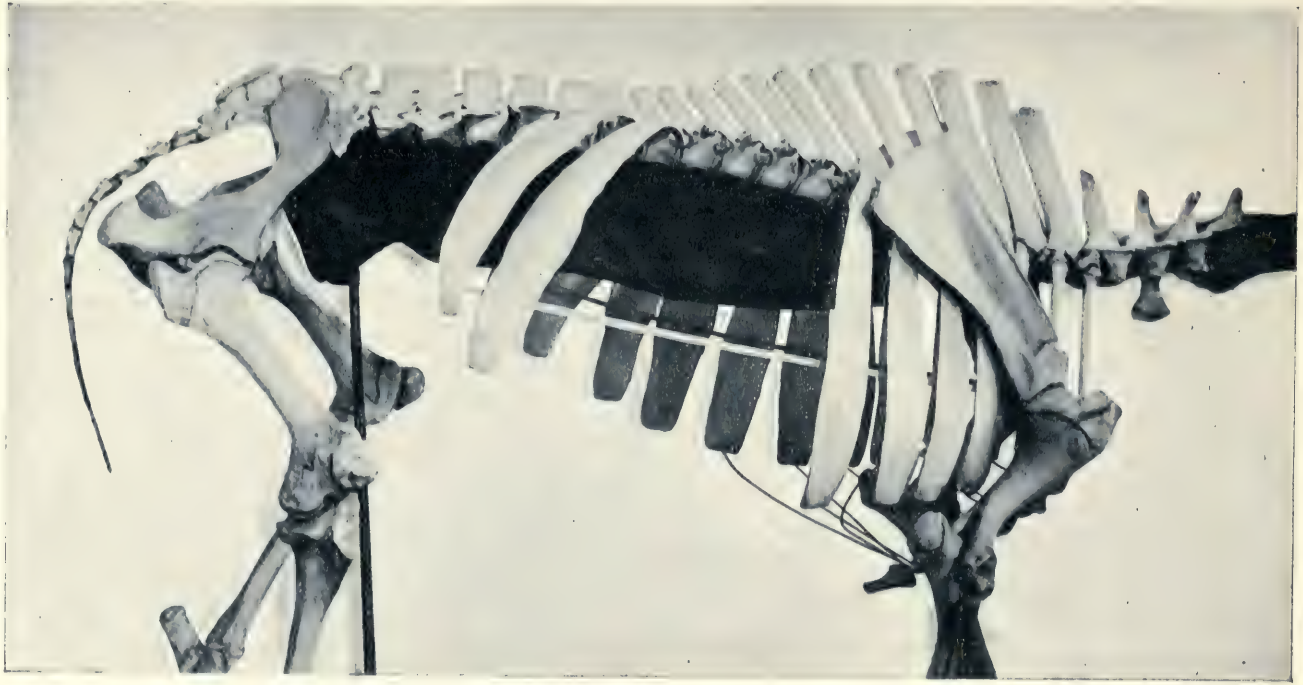


Fig. 28

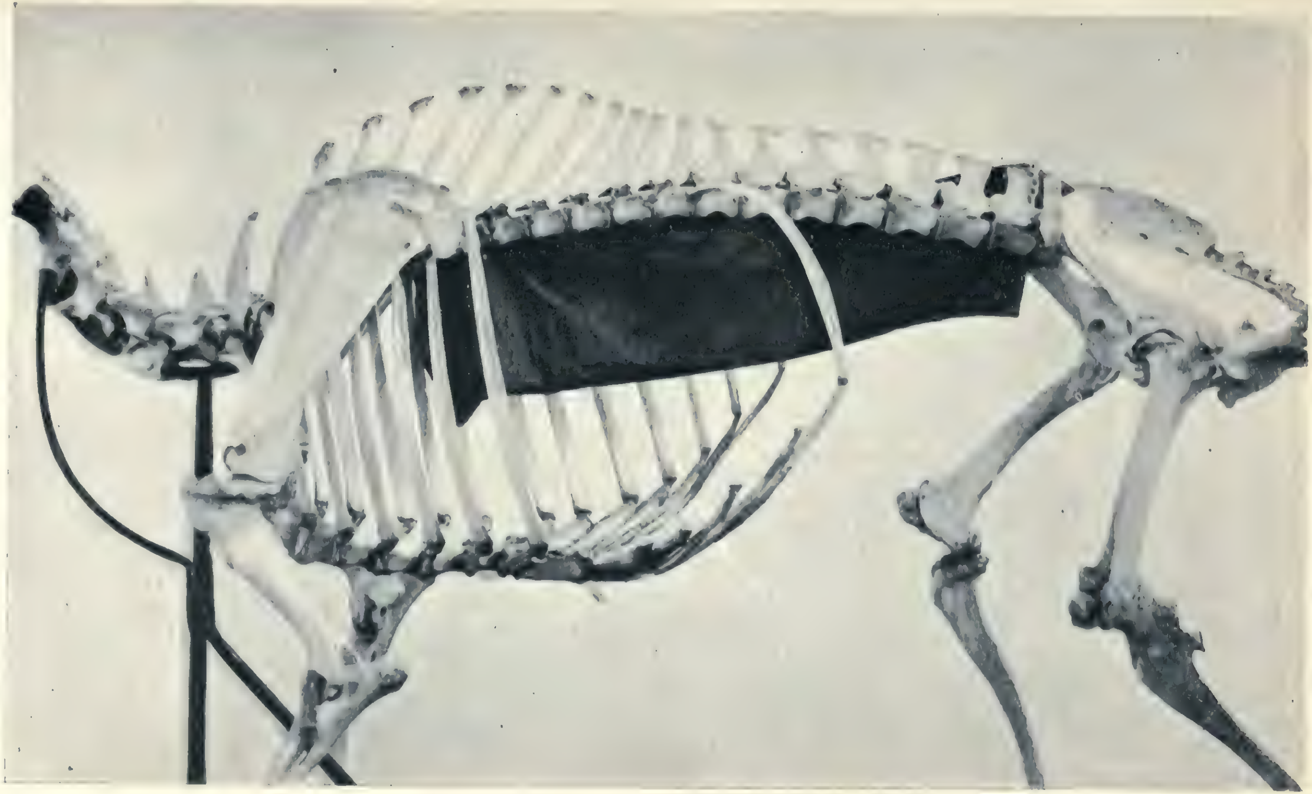


Fig. 29

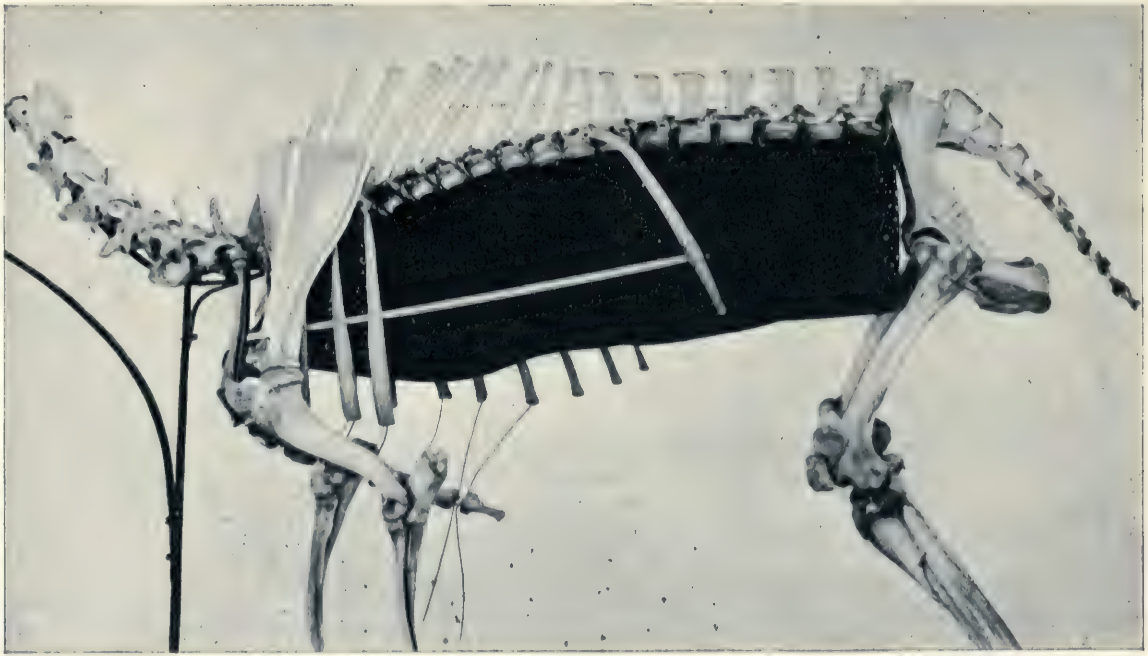


Fig. 30

black background. It is generally known that from the pachydermatous rhinoceros to the kaffir buffalo, and from the buffalo to the swift antelope, the mutual mobility of the vertebral bodies increases. And the regular decrease of the breadth of the spinous processes, *i.e.*, the increase of the distance between them, in the same order, may be considered as the expression of increase of mobility in a dorsally concave direction. Parallel to this mobility we see the concavity of the anterior outline of these vertebral bodies increase. In the last three animals (Figs. 28—30) the concavity of the lumbar vertebræ—just as the mobility—is also greater than that of the dorsal vertebræ, whereas in the rhinoceros (Fig. 27), in which the thick skin limits the movements of the lumbar part of the spine, this difference is not appreciable. A simple reasoning will show that the increase of mobility of the vertebral bodies is accompanied by a decrease of the pressure stresses in the transverse elements in the periphery of their cancellous tissue.

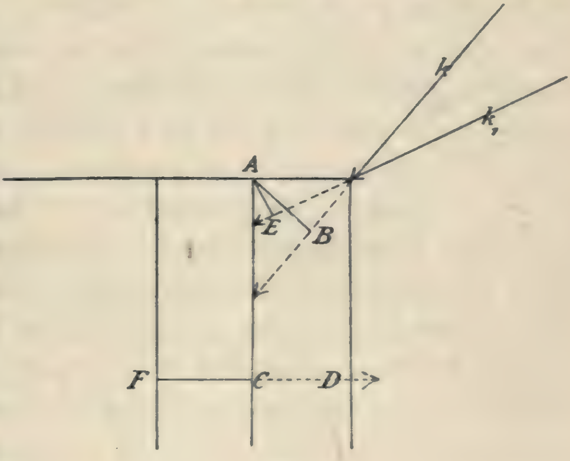


Fig. 31.

It needs no further argument to show that in proportion as the mobility of the spine—*i.e.*, the mutual mobility of the vertebral bodies—is greater, the resultant of the forces which act upon the border of the vertebral bodies, is on an average directed more obliquely, *i.e.*, departs more from the vertical axis. So, if Fig. 31 represents part of the upper half of a (schematic) vertebral body, and if it may furthermore be assumed that the forces acting on the border of the vertebral bodies, are transmitted by strips of bone to the axial elements situated more centrally—of which for convenience only a part AC is considered as if it were a turning staff—the moment of k on AC is $k \times AB$. Balance will be established as soon as in a transverse element FC a stress D is caused, the moment of which is equal to the moment of k, so, $D \times AC = k \times AB$. When, instead of k, a force k_1 comes into action a different stress D_1 will have to develop in the transverse element, and $D_1 \times AC$ will be $= k_1 \times AE$. In the first case $D = \frac{k \times AB}{AC}$ and in the second case $D_1 = \frac{k_1 \times AE.}{AC}$ So if $k = k_1$ and $AB > AE$, D will be $> D_1$.

Hence *the pressure stresses in the transverse elements in the periphery of vertebral bodies balancing the forces which act on the border of these bodies, are smaller in proportion as the latter are directed more obliquely.*

In the above we observed that in a schematic cylinder-shaped vertebral body the vertical (axial) bone elements would have upon the whole a greater tendency to bulge out—like the staves of a barrel—on weight bearing than to bend inward. They would, in other words, exercise more pull than pressure on the transverse elements which connect them mutually and with the axial elements situated more centrally. Now we see that *this pressure on the transverse elements decreases in proportion as the forces act more obliquely, and this may be the cause why these elements are maintained less in proportion as the mutual mobility of the vertebræ increases.*

Moreover, on a transverse bonestrip, *i.e.*, a bonestrip running parallel to FC, which is situated twice as near to A as is FC, a force will have to act, which is twice as great as D (or D_1) in order to balance $k \times AB$ (or $k_1 \times AE$).

In other words, the pressure evoked in the transverse elements of cancellous tissue by the forces directed obliquely is greater in proportion as the transverse elements are situated nearer the end surfaces, smaller in proportion as they are nearer the middle of the height (or width) of the vertebral bodies. So in this respect also the concave form of the lateral surfaces of vertebral bodies shows a parallelism with the intensity of the pressing forces. Where in the transverse elements the pressure is smallest, the concavity of the lateral surface is greatest. *Hence in the various degrees of concavity of vertebral bodies in man and animals we see the outcome of the fact that cancellous tissue elements lessen, or fail, wheresoever pressure stresses diminish or cease to act, i.e., a parallelism with pressure stresses.*

Nor is it difficult to find examples of this parallelism in the vertebræ of other animals. We have observed it in aquatic mammals as well as in the "amphicoelic" form of the vertebræ of snakes. In the latter the strong lateral movements of the spine in locomotion seem to determine the marked lateral excavations. *And the most instructive point of all this is that not only the transverse bone elements disappear, but also the vertical (axial) elements such as are present in the central part of vertebral bodies. Hence the existence of the vertical elements of cancellous tissue at least in the vertebral bodies, appears to be bound to the action of pressure on the transverse elements.*

In the formation of the elements of the convex side in the ankylosed knee (see Figs. 16—20 and pp. 22 and 23), a share could not be denied to vibrating movements. Therefore, it might be argued that in the transverse elements of cancellous tissue also pressure stresses might be evoked by such vibrating movements, whenever tension to which they had been exposed should suddenly be removed. Such vibratory motion, and with it the action of pressure on those transverse cancellous elements, cannot be denied. Further, in the case of Coxa vara it must be noted that the vibrating mass—a few small bone strips—is small and with it the pressure which can be caused by vibration. So no wonder that this vibrating pressure fails to maintain the transverse bone elements of cancellous tissue in the periphery of vertebral bodies.

Hence in the vertebral bodies of man (*and even of mammals and snakes*) *not only the transverse elements of cancellous tissue are failing which would coincide with the directions of tension, but also the vertical* (*axial*) *elements they would have to connect. Tension appears to lack the power of bone formation in the human vertebral bodies, in the normal ones as well as in the deformed and bent ones, the power which pressure appears to have in all cancellous tissue we examined.*

Surveying what the previous research has taught with regard to the formation of bone tissue, we find without an exception a contrast between the effect of tension and of pressure in all bones we examined: the femoral neck on being deformed to Coxa vara shows a thickening of the concave side, where pressure stresses increased, atrophy and rarefaction on the convex side, where tension stresses increased (Cf. Figs. 3, 4, 5 with Fig. 1). In ankylosed knees as well as in the ankylosed elbow (Fig. 34), where bone elements regularly develop along lines of evident pressure, the elements of tension are missing which would have to curve from the concave side along the convex and back again to the concave side. (Cf. Figs. 13, 16, 17, 18, 19, 20 with Fig. 15). And in the normal vertebral bodies of man and animals even the vertical cancellous elements appear to be absent wherever the transverse elements would have to meet tension only. In short, the contrast between the effect of tension and pressure on the formation of bone tissue appears not to be restricted to normal vertebral bodies of man and animals, deformed vertebræ and curved spines; but it also manifests itself in femur and tibia, in humerus and ulna. The thickening of bone elements on an increase of pressure, the wasting or disappearance on a decrease or disappearance of pressure stresses, in short the parallelism which we meet everywhere between the degree of pressure and the width of bone elements is without exception absent with regard to tension in all bones formed in cartilage which we examined. Nowhere—in the numerous bone sections we made and studied—did we meet with bone elements in a direction in which only tension had acted.

This contrast between tension and pressure in the effect on bone formation compels us to part with the prevailing conception concerning the "trajectorial" structure of the bones," with "CULMANN-MEYER'S crane hypothesis," with MEYER'S "calcaneum hypothesis," with ROUX'S notion regarding the structure of the ankylosed knee and last but not least with "WOLFF'S law" of the transformation of bones. All these theories have spread like weeds over the field of our science and obstructed the way to the knowledge of the formation of bone, of the structure, the form and the deformation of bones. The merit cannot be denied to WOLFF of having directed attention to transformation phenomena of bones, *i.e.*, to changes in the cancellous tissue of bones corresponding with changes of forces acting upon them. Nevertheless bone tissue does not behave according to his *law*, which ascribes the power of bone formation both to tension and to pressure stresses (cf. p. 5). Of WOLFF'S "Gesetz der Transformation der Knochen" (Law of the transformation of Bones) the "law" appears to be untenable, only the "transformation" remains, and even—as will be pointed out in the following pages—with regard to pressure stresses in a degree far more restricted than WOLFF believed. (Cf. Chapter VII.) And it is to be hoped that before any author in the future states that a bone deforms according to "WOLFF'S law" he will take the trouble to convince himself of the fact that behind the flow of words with which JULIUS WOLFF has published his "law" in the above quoted work, there is no proof whatever to show that tension stresses have the power of bone formation. In so doing he would be helpful in laying a foundation to the sound development of the knowledge of deformities.

But, whether future authors will submit to this trouble or not, from the facts given in the preceding pages clinicians may draw the lesson that wherever bone formation is to be promoted—as in fractures and bone transplants—bone formation cannot be on any reasonable ground expected from tension, though it can from pressure. And Chapter V. may tend further to show of what nature the pressure has to be in order that it shall be conducive to bone formation.

Though we cannot ascribe to tension the power of bone formation and must even deny such power on solid grounds, yet bone tissue is fit to withstand and transmit tension stresses. This need not surprise us any more than the fact that women will walk over roads made by men. *Still the fitness of bone tissue to withstand pressure is greater than that to withstand tension.*

RAUBER[1] found this relation = 4 : 3. And it is generally known also that bone fractures always start on the side where tension stresses develop, not on that of pressure stresses.[2]

If in the previous chapters we furnished grounds fo the conclusion that tension—in contrast to pressure— lacks the power of boneformation, the following chapter will serve as a further test to this assumption, since th structure of the cancellous tissue of bones formed in cartilage will appear to be easily understood—roughly at least—if it is considered as being composed of mere pressure elements.

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[1] RAUBER, Elasticität u. Festigkeit der Knochen, 1876. Quoted after O. MESSERER, Ueber Elasticität u. Festigkeit der menschlichen Knochen, Stuttgart 1880.

[2] CHRISTEN, Die Entstehung der Diaphysenbrüche. Verhandlungen der deutsche orthop. Gesellschaft. XIII Kongress, S. 12.

It is well known that the pressure forces acting upon an elastic body, cause tension stresses in the direction at right angles to the pressure. So the bone tissue is fit to bear not only pressure but also tension in directions at right angles to the pressure. But for this power the bone tissue would be apt to develop fissures parallel to the pressure, longitudinal fractures, which practically belong to the exceptions, and are known as "KRÖNLEIN'S fractures." So since it is a function of bone tissue to resist tension at right angles to pressure as well as to resist pressure, it may seem remarkable that nevertheless tension stresses acting at right angles to pressure fail to produce bone formation (see pp. 42-44). In fact any deeper insight is failing here. We may only point out a certain resemblance bone tissue in this respect shows to tendinous tissue, in which tension acting in the direction of the tendons, evokes pressure stresses in the directions at right angles to the tension ; but without, to all appearances promoting the formation of bone tissue. If we should call the act of resisting pressure the primary function of bone, and the act of resisting tension its secondary function, and reversely with regard to tendinous tissue, we might briefly express this by saying *only the primary function of bones and tendons forms a trophic stimulus.*

CHAPTER IV.

CANCELLOUS TISSUE COMPOSED OF PRESSURE ELEMENTS.

A. Conditions for origin and existence of cancellous tissue as such.

Before inquiring into the way in which cancellous tissue is built up, we shall have to find out the conditions for its origin and its existence.

The tube form of the diaphyses of long bones ensures for the material the greatest possible firmness and limits the chance of bending, folding or fracturing to a minimum. The danger of bending, folding or fracturing is upon the whole greatest in the middle of the diaphyses. Here, indeed, besides the stresses caused by direct pressure, those stresses must be resisted which are evoked by a bending of the bone and which decrease from the middle to the ends. So in the middle of long bones relatively great stresses are transmitted through relatively small transverse sections. And in this we shall find a ground for the fact that the wall of the diaphyses is of a compact structure. When, therefore, after a fracture of a diaphysis, the parts grow together so as to have contact over an area which is larger than normal, and thus the stresses are transmitted from one osseous part to the other through enlarged transverse sections, small holes are seen to develop on the bone substance at the site of junction. A tissue forms which though a little coarse, has the appearance of cancellous tissue (see Fig. 32). We then see cancellous tissue develop from compact bone by absorption of certain parts so that the transverse section, which remains for transmission of pressure stresses from one osseous part to the other, becomes smaller. We may assume that this change is brought about by the absorption of superfluous material, whilst only such parts as are needed for transmitting the stresses are preserved by the "trophic stimulus of function."[1] This process may, with ROUX, be called "Teilauslese"—or possibly no less correctly "*functional selection.*" But whatever name may be given to this phenomenon, *we note that in succession to a primary enlargement of the transverse section compact bone changes into cancellous tissue.*

Essentially the same phenomenon is observed in normal long bones where the compact bone of the diaphyses passes into the cancellous tissue of the articular ends. There, too, an enlargement of the transverse section is noted. In the first place because the articular surfaces as a whole serve for the transmission of pressure in contrast with the cross sections through the diaphyses. In these the central part inside the bony ring, naturally lacks material for such transmission. In the second place also on account of the trumpet-like thickening which long bones show at their ends. How this thickening comes into existence must for the present be left out of consideration. It may suffice to observe that it enhances the stability of the joint. Think, for instance, of the lateral mobility of the knee joint if the thin continuation of the diaphyseal tibial and femoral tubes should meet without widening out. Be this as it may, from the diaphysis to the articular ends of long bones we find an enlargement of the sectional area, and together with it a transition of compact bone into cancellous tissue.

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[1] The expression is derived from ROUX.

What the malunited bone fracture (*Fig.* 32) *shows at different* TIMES *at the same* PLACE, *long bones show in different* PLACES *at the same* TIME, *viz., the transition of compact bone into cancellous tissue where the transverse section enlarges* which transmits the pressure.

We may, of course, imagine conversely that in normal long bones cancellous tissue passes into compact bone by a lessening of the transverse section, and in this sequence we also observe the transition of cancellous tissue into compact bone at different *times*, in a lessening of the transverse section. In the most evident way this is shown in ankylosed joints.

In the preparation represented in Fig. 33 the articular surfaces of the knee joint have disappeared, and the femur and tibia show bony union. Fig. 33a represents the transverse section made through the ankylosis between the patella and the femur, both of which have lost their articular cartilage. Fig. 33b is a frontal section of the tibia in which part of the transverse section is visible fitting to Fig. 33a. So it has been turned with regard to the latter through an angle of 90° and then been photographed. Now we see that the diaphyseal tube of the tibia is continuing its course through the cancellous tissue of both tibia and femur on to the diaphysis of the femur, or reversely. The small area of the previous cancellous tissue, which transmits the pressure from the diaphyseal tube of the tibia to that of the femur, merges into compact tissue; the rest of the cancellous tissue, on the inner and outer side, atrophies. *So here it appears that cancellous tissue may pass into compact bone as well as conversely just as*—the pressure remaining the same—*the transverse section transmitting the pressure either becomes smaller or larger.*

It must be observed also that the cancellous tissue in the immediate proximity of the compact newly-formed tube has in some parts almost totally disappeared, whilst

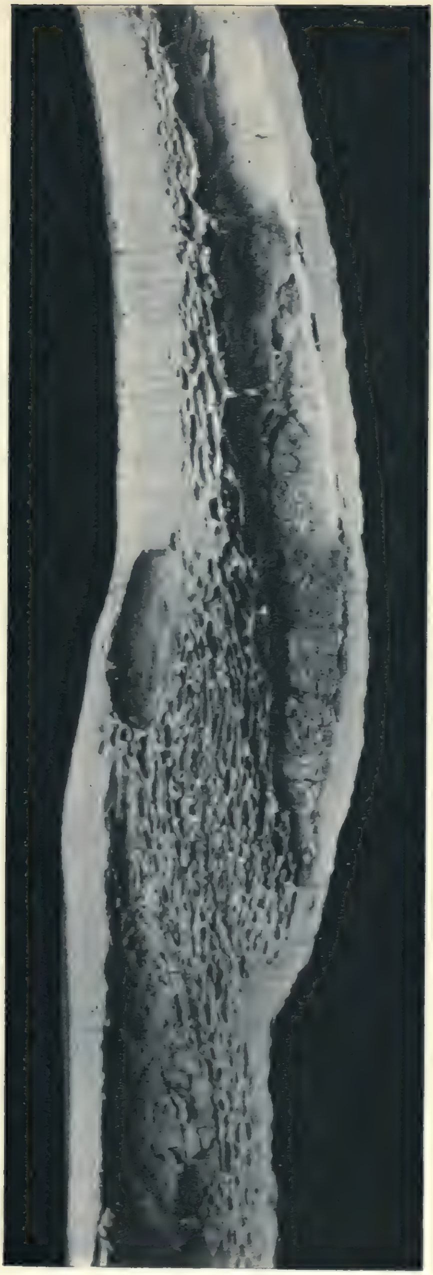

Fig. 32

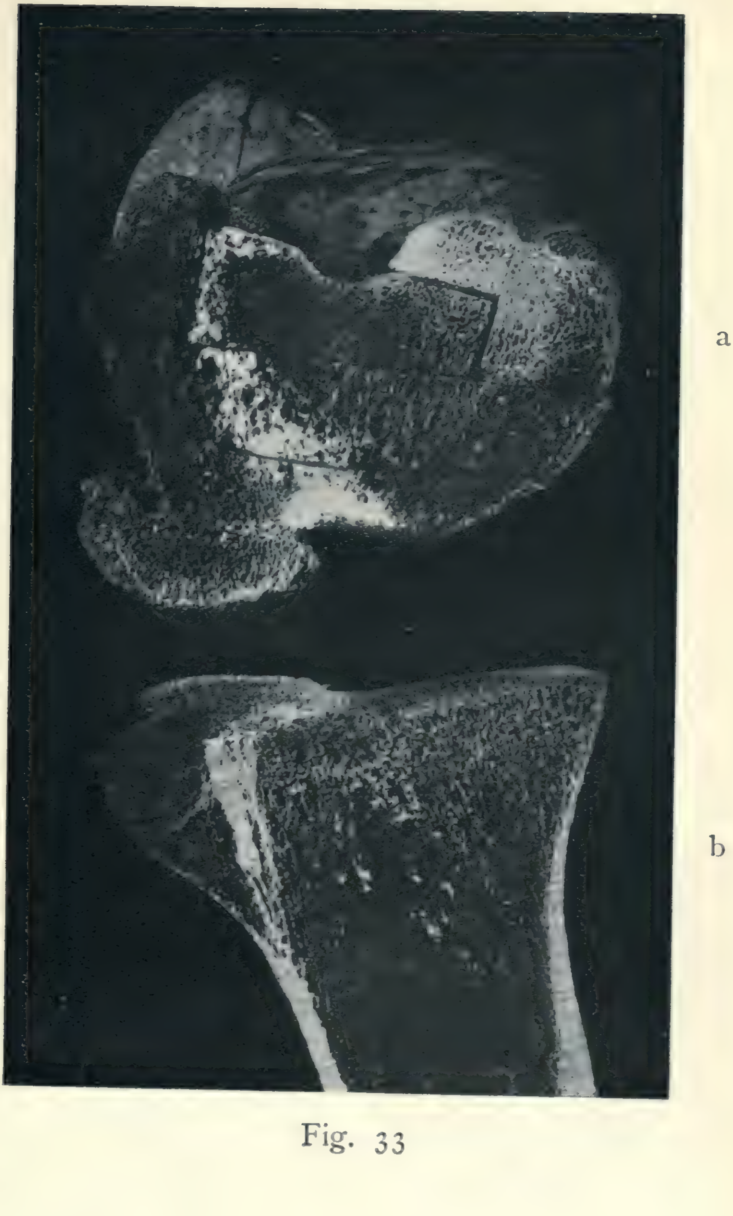

Fig. 33

a thin layer of the periosteal bone in the periphery has been better preserved, thus maintaining the external form of tibia and femur. This phenomenon will be dealt with later (see pp. 96-101). In the present only the transition of cancellous tissue into compact bone is of interest—a process which we also observed more or less completely in the ankylosed elbow of Fig. 34 and the ankylosed hip (Fig. 35, cf. Fig. 1). It appears to go hand in hand with a reduction of the transverse sections conducting the forces acting upon the bone, just as reversely the transition of compact bone into cancellous tissue coincides with an enlargement of the transverse section transmitting the stresses.

For the reader who might be of opinion that some of the bone elements in the above figures (Figs. 34 and 35) might be ascribed to tension stresses, a few remarks may be made.

In the ankylosed *elbow* (Fig. 34) pressure stresses have been evoked along the concave side, whenever the arm acted as a support; along the convex side, whenever the hand carried a weight. One or the other happened alternately, whenever the sudden termination of either of these functions caused vibrating movements in the humero-ulna. Moreover, it may be considered probable that the biarticular heads of biceps and triceps—which will survive in inflammatory conditions of the elbow (cf. p. 23), have transmitted pressure stresses in the posterior or the anterior parts of the bones. These various pressure stresses may therefore have had a share in the formation of the firm bony tube which constitutes the humero-ulna. Only the region of the olecranon is atrophic, so that part of it could easily disappear by injury (beyond our control). It is the area in which after the development of the ankylosis the long—biarticular—head of the M. triceps brachii could cause tension stresses only.

That the convex side of the femoral neck in the ankylosed hip (Fig. 35) is thickened and converted into compact bone, might at first sight suggest the idea that here an area in the bone tissue is encountered in which tension stresses have indeed led to bone formation. The pelvitrochanteric muscles, which normally produce the pressure stresses in the direction of the femoral neck, monarticular as they are, have been relieved of their task and atrophied after the bony union (cf. p. 23). Yet pressure stresses cannot be excluded. It must be borne in mind that in walking the pelvo-femur is apt to bend in the direction of adduction whenever the leg of the sound side is lifted. The trunk then bends over to the affected side, in order to bring the centre of gravity perpendicularly over the plane of support of the foot on that side. The weight of the upper part of the trunk, thus bent over, balances the weight of the pelvic half of the sound side and its appendant leg.

It needs no argument to show that in doing so the femoral neck can be raised—even though slightly—on the affected side (in the direction of coxa valga), causing pressure stresses in the *convex side of that neck,* which we find converted into compact bone. Moreover, adduction movements in the pelvo-femur which end suddenly, will cause vibrating movements which are associated with pressure stresses in the convex side of the femoral neck. These elastic forces could be neglected in coxa vara, where the femoral head is movable in its socket and so the mass of the vibrating part small (cf. p. 24 and 46). Here, however, where the heavy pelvis and trunk are firmly connected with the femoral neck by bone substance, the moment of the elastic forces is great, and must not be neglected any more than in ankylosed knees.

Striking to the eye are the *bone trabeculæ which connect the concave and convex side of the tube-wall of the ankylosed elbow* (in the area of the humerus) at oblique angles. We meet with them *in all ankyloses that have developed in any position other than extension.* They are visible in Figs. 19 and 20. Fig. 33b shows them cut obliquely as white spots. Fig. 35 shows them in the curve of the femoral neck. In order to understand their development, we must consider that a bent rod or tube on farther bending, or on folding, is flattened in the area of the bend or fold, namely, in the plane of the bending. *The concave and the convex side* of the (previous) humerus of Fig. 34 in other words tried to approach each other whenever the humera-ulna increased its curve, so that cross sections at the site of the bend drew nearer to the form of an oval having the short dimension in the plane of bending. We may therefore assume that the oblique trabeculæ indicate the direction in which pressure stresses were caused in the original elements of the cancellous tissue. These pressure stresses may have led to their maintenance and thickening, while the surrounding cancelli atrophied. In the ankylosed knee of Figs. 16, 17 and 18, a remnant of the joint line is present as a deep notch at the back. Therefore this bone tube will have been less flattened antero-posteriorly in bending. Accordingly we find the antero-posterior trabeculæ limited almost exclusively to the area of bony union between femur and tibia, *i.e.*, to the area where the strongest bending may be assumed.

Not one of the bone elements, even in these preparations, can therefore be ascribed to tension, because the action of pressure along the existing bone elements can nowhere be excluded.

The development and the existence of cancellous tissue appears to be dependent on a relatively large area of the transverse section transmitting the pressure; and, as in each position which two joint surfaces may occupy

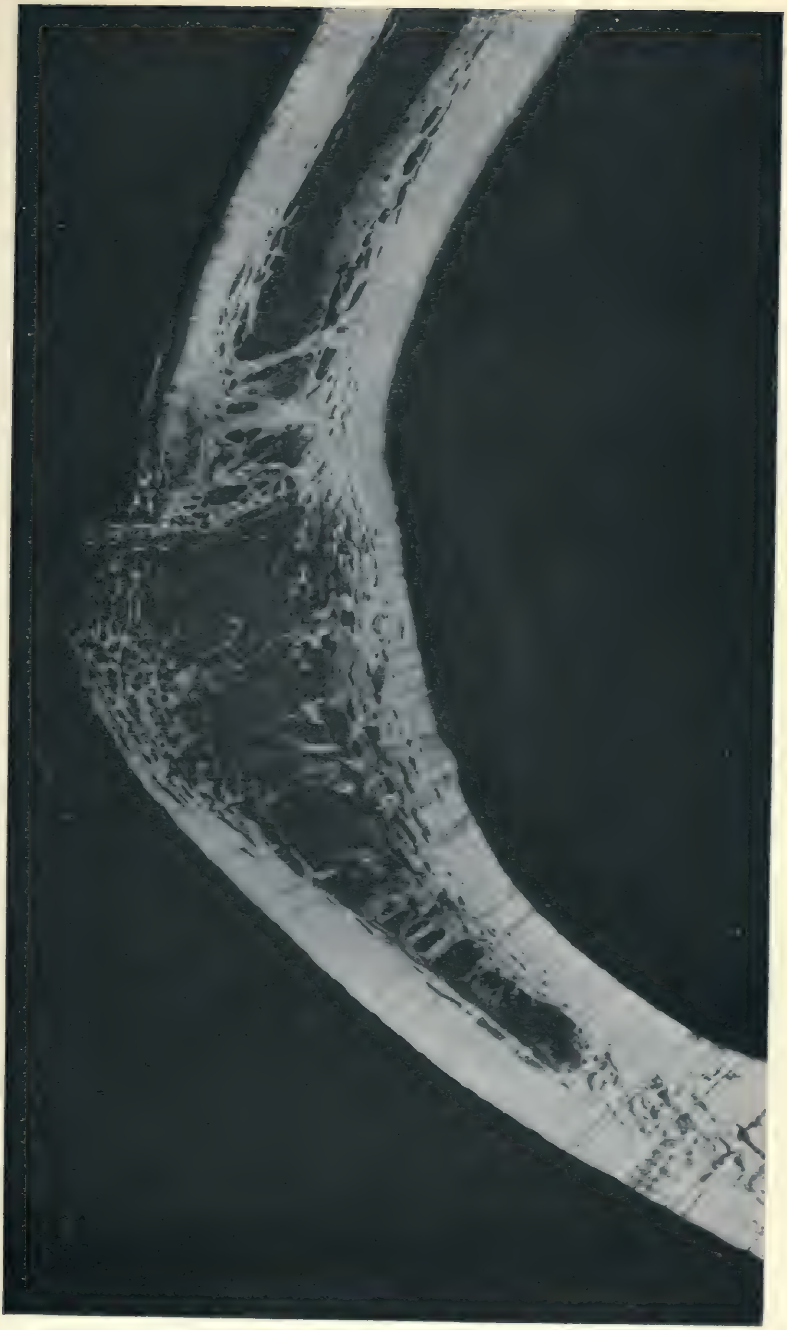

Fig. 34

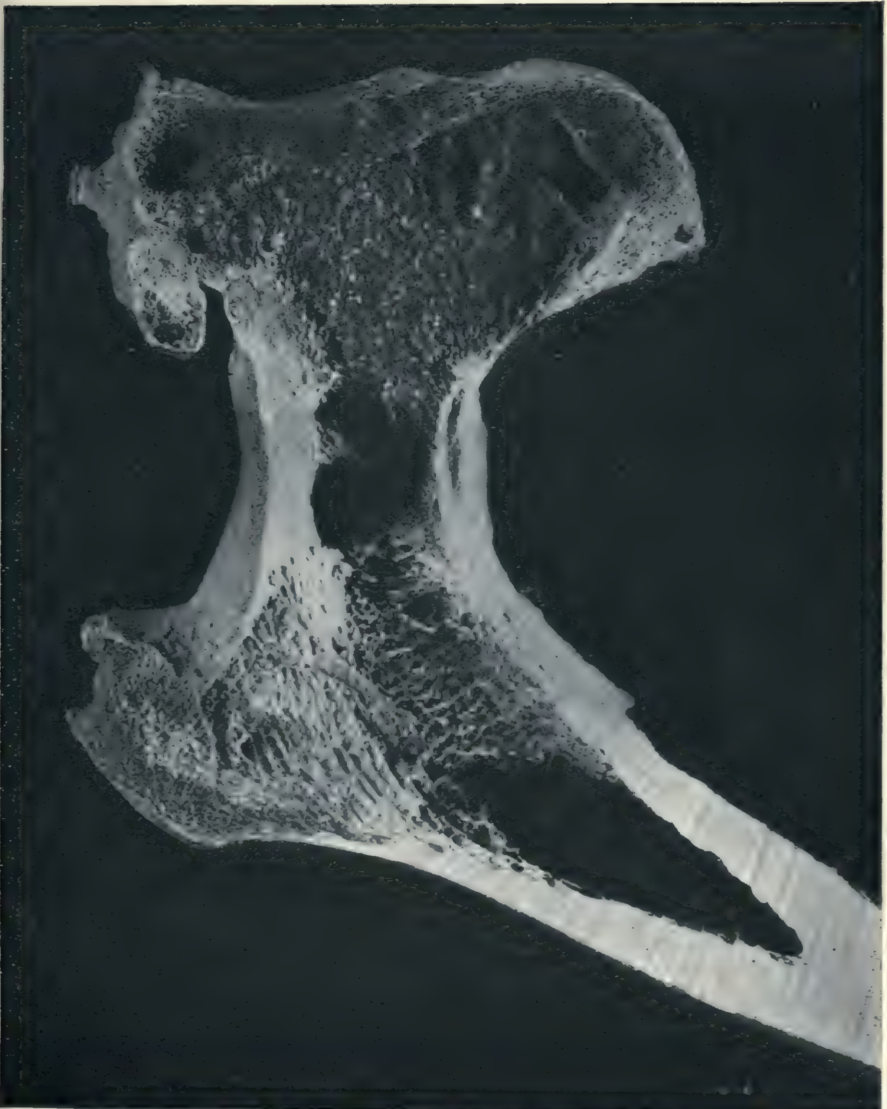

Fig. 35

mutually, pressure stresses are caused and must therefore be resisted, the normal structure of cancellous tissue must be narrowly related to the normal mobility of the joints.

Summing up what previous chapters have taught concerning the *structure of cancellous tissue,* we come to the following conception: *the lines along which pressure stresses run through bones, are represented by fasciculi of bone elements which fuse whenever the pressure lines are close together, but leave spaces between them whenever the pressure lines pass through relatively large transverse areas* —as in joint surfaces. In each position of the joint surfaces a series of pressure lines passes from one bone to the other. So in the first place the number of these positions, *i.e., the mutual mobility of the joint surfaces determines the texture of cancellous tissue.* In the following chapter we shall therefore try to find out in what way in articulations with one, two or three axes, the course of the pressure stresses varies and to trace the connection with that of the bone elements which compose the cancellous tissue.

B. The way in which the pressure elements compose cancellous tissue.

In the first chapter we mentioned that previous investigators have tried to lay down the rules according to which cancellous tissue is constructed. That in so doing they wrongly ascribed part of the cancellous tissue to tension stresses may have become evident in that and the following chapters and may be now left undiscussed. Most of the authors, moreover (MEYER, WOLFF, ROUX, a.o.), took into account only the static pressure from the body weight in the erect attitude. ZSCHOKKE attracted attention to the fact that the dynamic pressure of muscle action is often far greater than the static, and therefore, must not be neglected in the explanation of the texture of cancellous tissue.

The correctness of this opinion may be illustrated by a simple example. In standing on one leg with the heel raised from the ground, the body weight is entirely transmitted to the ground through the metatarsal heads, and the latter are mutually pressed with the same force, f.i. 60 Kg. This, too, is approximately the force with which the body weight presses the tibia on the arch of the foot. Now the quadriceps in order to maintain the tip-toe position has to balance the pressure against the matatarsal heads. This muscle acts with respect to the turning axis of the foot joint on a lever arm ± 3 times as short as does the pressure of the ground against the metatarsal heads. It must therefore develop a force which is 3 × as great, *i.e.*, transmit a pressure thrice as great through the skeletal parts situated between its points of origin and insertion. Hence the tibia has to bear a pressure of $60+3\times60=240$ kg.[1]

Nearly all later investigators have indeed ascribed an influence both to the dynamic and the static pressure. All, however—ZSCHOKKE included—fail to give a dynamic explanation of the texture of cancellous tissue instead of the untenable static conception.

SOLGER[2] (cf. p. 5) deems "the basis of the facts on which to found a new theory of the bone elements not nearly wide and deep enough." If in the following we shall give a new theory to that effect, it will be based on the facts we have learned in the previous chapters and which we will try to complete in the following ones. However, we must not fail to remind the reader hat the *transmission of stresses in elastic bodies is not ccurately known to physicists, and that for this very reason ach explanation of cancellous tissue*—which actually implies he knowledge of these stresses—*must for the time being emain only a rough approximation.*

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[1] Cf. CHRISTEN l.c.

[2] B. SOLGER, Der gegenwärtige Stand von der Knochen-Architektur.—Untersuchungen zur Naturlehre, JAC. MOLENSCHOTT, XVI. Bd. S. 213.

The pressure of muscle action and body weight is—as vas mentioned above—transmitted by the joint surfaces ot in the erect attitude only (cf. pp. 55 and 56), but in very position a bone can occupy. Material must thereore be present to withstand the pressure stresses in every ne of these positions. Let us, for instance, take the lower nd of the femur, and consider it turning upon the orizontal upper surface of the tibia. When we start from he knee bent at a right angle, and the femur is raised to he vertical position by contraction of the muscles in ront, we see that the point of contact of the femoral ondyles with the tibia changes each moment, in the ent position the back of the femoral condyles being in ontact with the tibia, in the extended position the lower art of these condyles. Hence, the pressure stresses radiate ach time from a point situated more to the front.

In what way the distribution of the stresses takes place rom each of these points, is a complicated problem which, owever, for the present purpose needs no complete olution. It is certain that *from each point of contact he stresses radiate upward and forward more or less in he form of a cone*—possibly a bent one—*and at the same ime the strongest stresses are directed to the anterior and rontal aspect of the diaphysis* where the moving forces of the M. quadriceps) act on the patella. The cone shape f the chief radiating pressure stresses may therefore be onsidered to have a flattening on both sides. In other vords it approaches the form of a fan which is directed pwards and forwards. So during the described extension novement in the knee from each of the points of the femoral condyles which successively come into contact with the tibia, a series of pressure lines radiate approximately in the shape of a fan which has to be represented by bone elements. *When from a series of points of the outline of the antero-posterior section of a femoral condyle such "fan shaped" radiating lines are drawn, they appear to cross in many places ; and they will on a sufficient increase of their number occupy nearly the whole of the area of the drawing, leaving apertures between them which are small and approximately circular near the articular surface larger and more oval at a distance.* (Fig. 36.)

In agreement with this we find that the *cancellous tissue in the femoral condyles* shows a preference in the arrangement of its elements for the direction in which the pressure stresses are strongest, so that it can schematically be considered as being *composed of numerous bone plates running antero-posteriorly from the trochlear surface in front to the condyles behind* (see Figs. 37 and 38). Seen from the side, these bone plates do indeed present *apertures which are small and round near the articular surface, and seem to become larger and more oval in proportion as they are farther away from it* (Fig. 39). Therefore, these openings in the bone plates or lamellæ are to be considered as places through which no pressure stresses have been transmitted. There, just as in the spaces between the plates, the trophic stimulus of function has been failing And we are forced to assume that during growth these apertures continually change their form and place, *i.e.*, that at different periods the trophic stimulus of the pressure stresses acts on different points of the bone plates.

Observe that the direction of the plates does not coincide with that of the turning plane of the femur, which should be expected if gravitation as such should determine their direction. They converge from the back of the condyles to the trochlear surface in the very direction in which

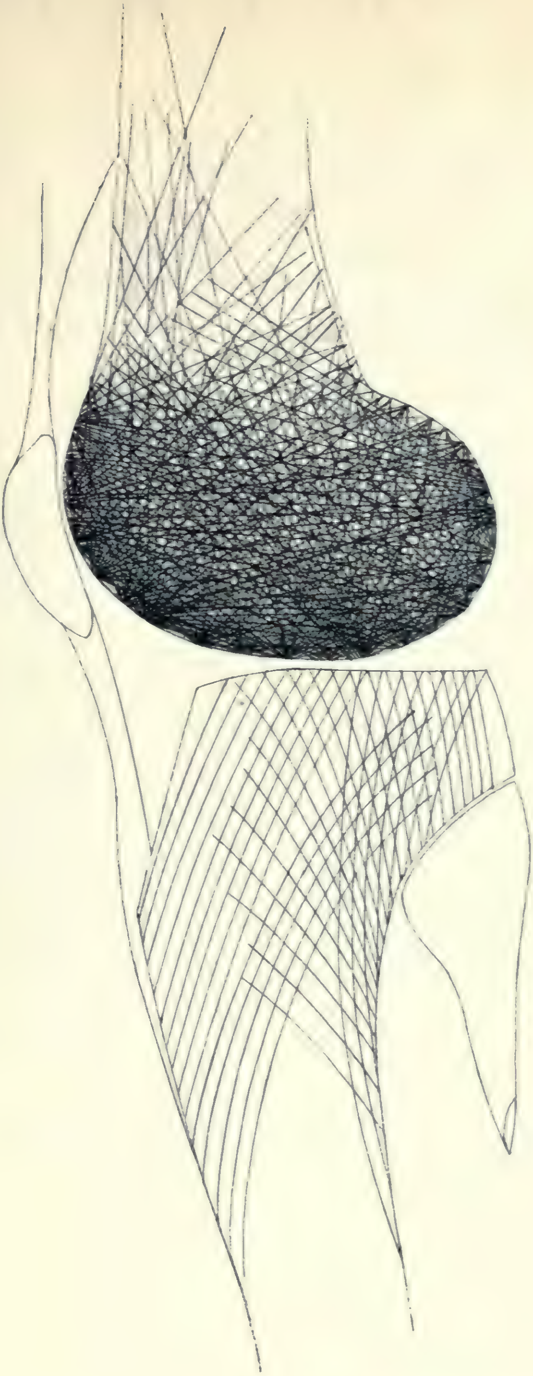

Fig. 36

The femoral end of this scheme represents the structure *in* the condyles (cf. Fig. 43).

The tibial end represents the structure *between* the condyles (cf. Fig. 45).

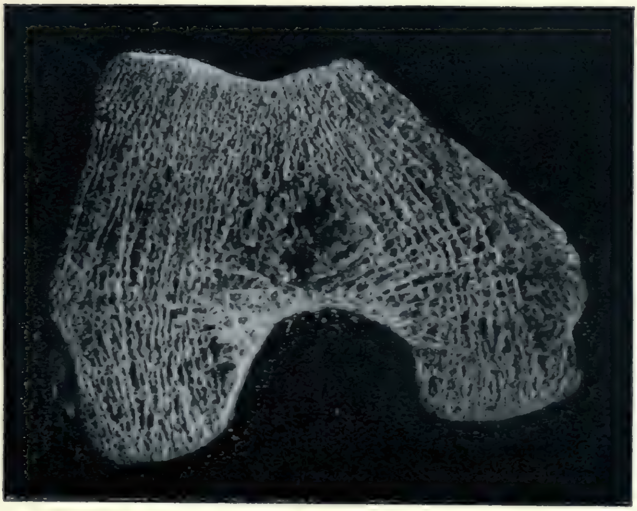

Fig. 37

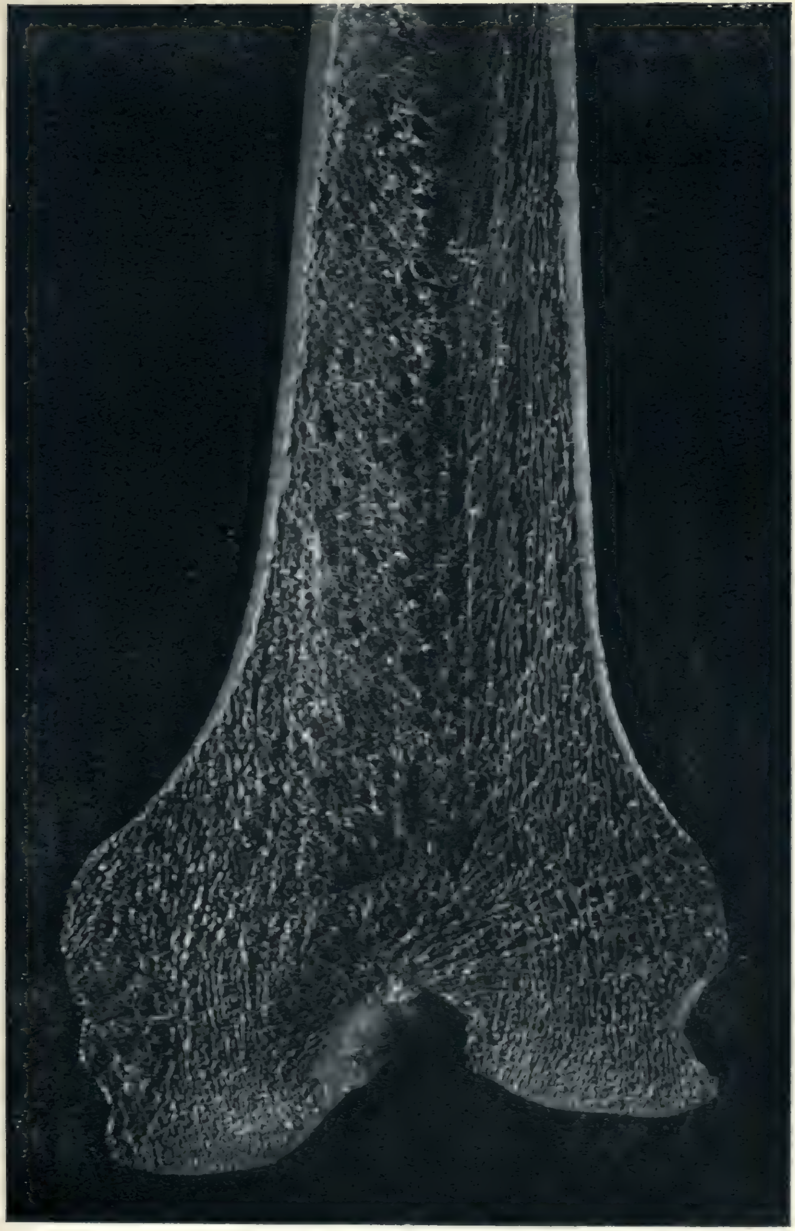

Fig. 38

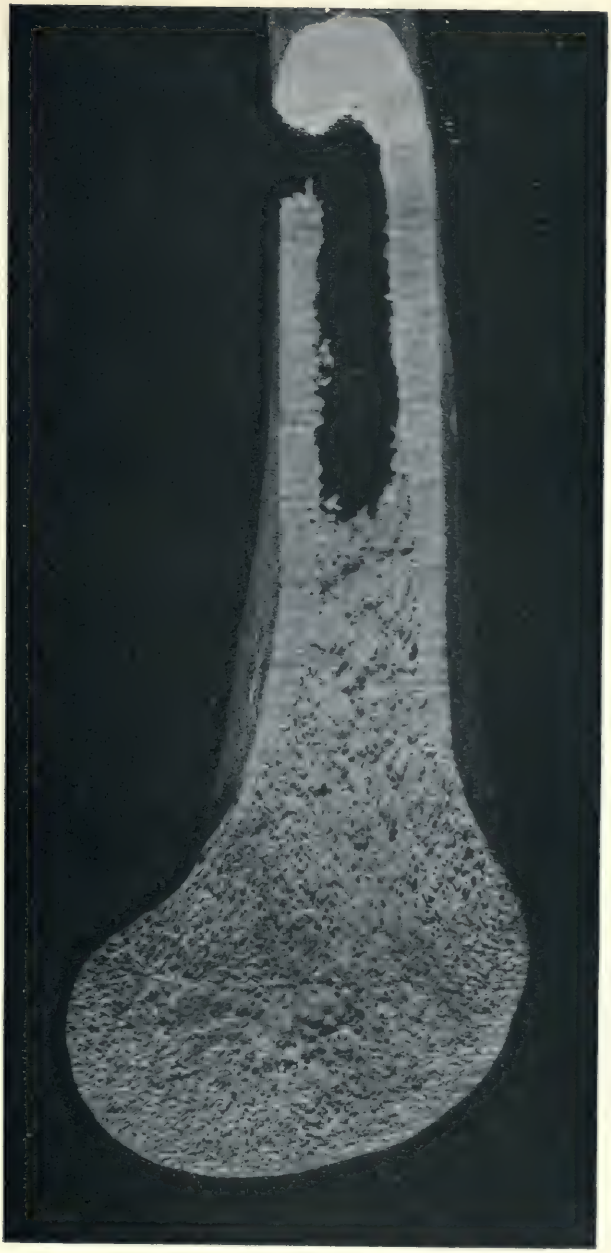

Fig. 39

he forces of the extensor muscles are transmitted to the oint surfaces. Hence, as was anticipated, *muscle action ppears to have the decisive effect on the structure of cancellous issue in the knee.*

On page 20 we pointed out that the boneplates of ancellous tissue never have a perfectly even or smooth spect, but present irregular undulations, so that their nutual distance varies at different places. In some laces they come into contact and seem to fuse or to cross. n other places a plate seems to split up into two (Figs. and 10). Besides these splittings, meetings and crossings f the bone plates, we meet with a number of *bone trabeculæ* vhich here and there span the distance of the plates and onnect them. They are by no means always at right ngles to the surface of the plates (cf. p. 19), but are often lirected obliquely (see Fig. 10). They are the *secondary r accessory elements* which prevent the *primary or essential ressure elements* from bending sideways and give them nutual support. We observed in the above that they eem to occur upon the whole in places where convexities n the plates face each other, so that pressure transmitted y the plates will tend to lessen their distance and shorten he transverse bone strips, *i.e.*, cause them to bear pressure see Fig. 12, p. 20). However, we lack the certainty that his holds good for all transverse and oblique trabeculæ, he more so as the undulations of the plates often show pposite directions in the plane of the section and in another arallel plane close by. It is the transverse bars or seconlary elements which give to the frontal and transverse ections of the lower femoral end very nearly the aspect f latticework. They led previous investigators to think hat they answered to the direction of greatest tension; nd their development was considered to be due to the ction of tension stresses (cf. p. 19). To us they are oubtlessly partly, and possibly all, bearers of pressure stresses. The reasons for this assumption have bee put forward in the previous chapters.

The microscopical structure of the antero-posterio bone plates in the lower femoral end fully agrees wit the assumption that they are the result of a fusion o bone trabeculæ which in the plane of these plates cros in the most varied directions. It is well known that i compact bone the longitudinal axis of the bone-corpuscle largely coincides with the direction of the pressure stresse *i.e.*, runs parallel to the axis of the diaphysis. On studying the bone plates of the lower end of the femur wit the magnifying glass, we *find* the axis of the *bone corpuscle* upon the whole lying in *the plane of the plates*; but in the they *run in all directions*. In the secondary element the oblique and transverse bars, the longitudinal axi again coincides with that of the bone trabeculæ. Tha the apertures in the lamellæ are rounded just as the place where transverse and oblique bars meet the plates, s that the borders of these apertures and the places of meeting are bordered by a regular series of bone corpuscle whose longitudinal axis runs parallel to the circumferenc is in no contradiction whatever with the above.

From the course of the bone elements in the lowe femoral end it is patent that ALBERT[1] has unjustly described them as a series of bottle bellies fitting one in th other; and that he was still more in error in terming th above bone plates "contour lamellæ." Fig. 37 show that they follow the lateral "contour" only, not th anterior and posterior ones. ALBERT, moreover, represents the surface of a bone plate as if it were compose of elements crossing at right angles. Both the macroscopical and the microscopical structure and its connectio with function appear to have escaped ALBERT'S attentio

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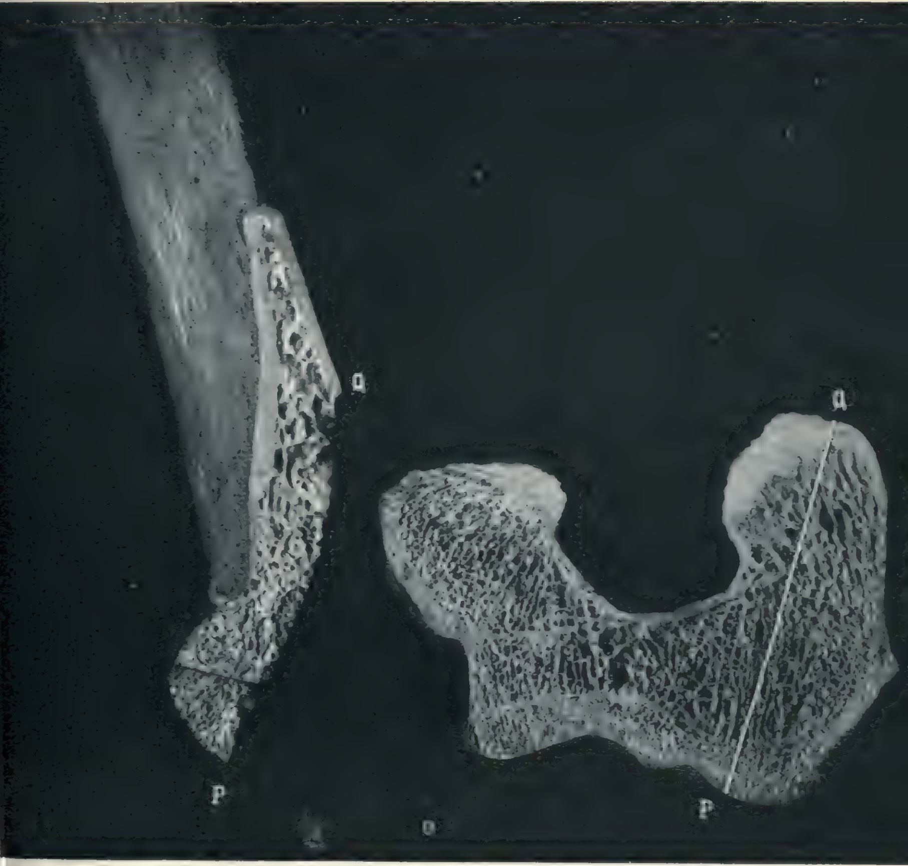
[1] E. ALBERT. Einführung in das Studium der Architektur der Röhrenknoche Holder. Wien, 1900, p. 47, Fig. 56.

Indeed he says (p. 48 l.c.): "What mechanical meaning this texture may have, will have to be found by later research."

We must also direct attention to the *series of diverging bone trabeculæ radiating from the intercondyloid fossa in the lower femoral end.* (Fig. 37.) ALBERT has called it a "radiant," and described the bone strips as "lamellæ" or plates, comparing them to the "leaves of a book which meet in a fold at the back" (p. 20, l.c.). If this were correct, the longitudinal, frontal section of the femur would have to show a few leaves of the book partly or entirely on their flat surface. However, there too, we see them as a "radiant" (see Fig. 38). Those who wish to carry on ALBERT's comparison must therefore imagine the book divided at right angles to its longitudinal direction by a large number of sections, into thin strips, so that they remain connected only at the back of the book. The back must furthermore be considered as bent lengthwise, with the concavity backward and coinciding with the antero-posterior surface of the intercondyloid fossa. This, by the way, does not render the name "radiant" less suitable for this system. It may be considered probable that on lateral movements in the upper femoral end, the intercondyloid fossa will tend to lengthen upwards and laterally, thus causing lateral strips of the radiant to be shortened, *i.e.*, to bear pressure, just as well as on movements directed medially, radii of the medial radiant will be made to resist pressure. This holds good for the extended position as well as for positions of flexion. So we may assume that on every one of these positions a series of bony radii rising from the intercondyloid fossa, will meet pressure on lateral movements of the femur.

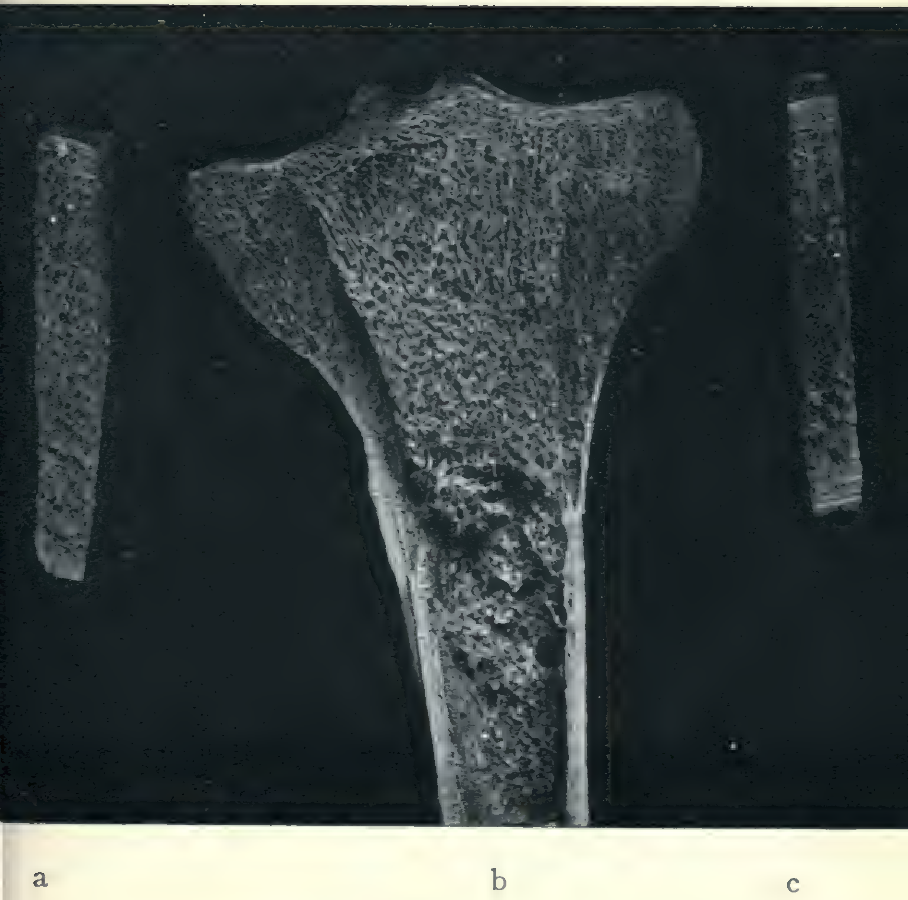
The antero-posterior bone plates in the lower extremity of the femur, with the oblique and transverse bone strips connecting them, represent the characteristic type o *rotation structure* which we observe in the *convex side o monaxial joints.* We also find it for instance in the *lowe end of the humerus.* Fig. 40b represents its frontal section and Fig. 40a is the frontal part appertaining to it, turned through an angle of 90° and photographed, after part of it had been removed from it by an antero-posterior cut The position of this saw cut is indicated in Figs. 40a and 40b by the lines *PQ*. So the two parts a and b being co-adapted, the lines *PQ* will coincide. A preference for the arrangement of the plates in the direction of movement is evident. So here, as in the knee, we meet with more or less complete bone plates or lamellæ, which are shown from the side in Fig. 40a and in Fig. 40b on a transverse section. Near the joint line the plates rise from the joint surface corresponding more or less with the direction of movement. A little higher they alter their course. And though we are unable to make an accurate analysis of the direction of the stresses which have been acting in the bone during life, it may be considered probable that here, as in the knee, the pressure of muscle-action has determined the structure of the cancellous tissue. In the elbow for conceivable reasons the pressure of gravitation falls in the background, more even than in the knee, as compared with muscle-action, which correspondingly steps into the foreground.

In the *concave side of monaxial joints* the bone elements are also arranged so as to coincide with functional pressure stresses. In Fig. 41b, for instance, two frontal sections of the upper end of the tibia have been superposed. From the uppermost frontal one, lateral parts (a and c) have been removed by antero-posterior saw cuts and been photographed on either side of b, after having been turned through an angle of 90°. Now in a and c the bone plates are seen more on their side surface, in b more on their edges.



a b

Fig. 40



Eig. 41

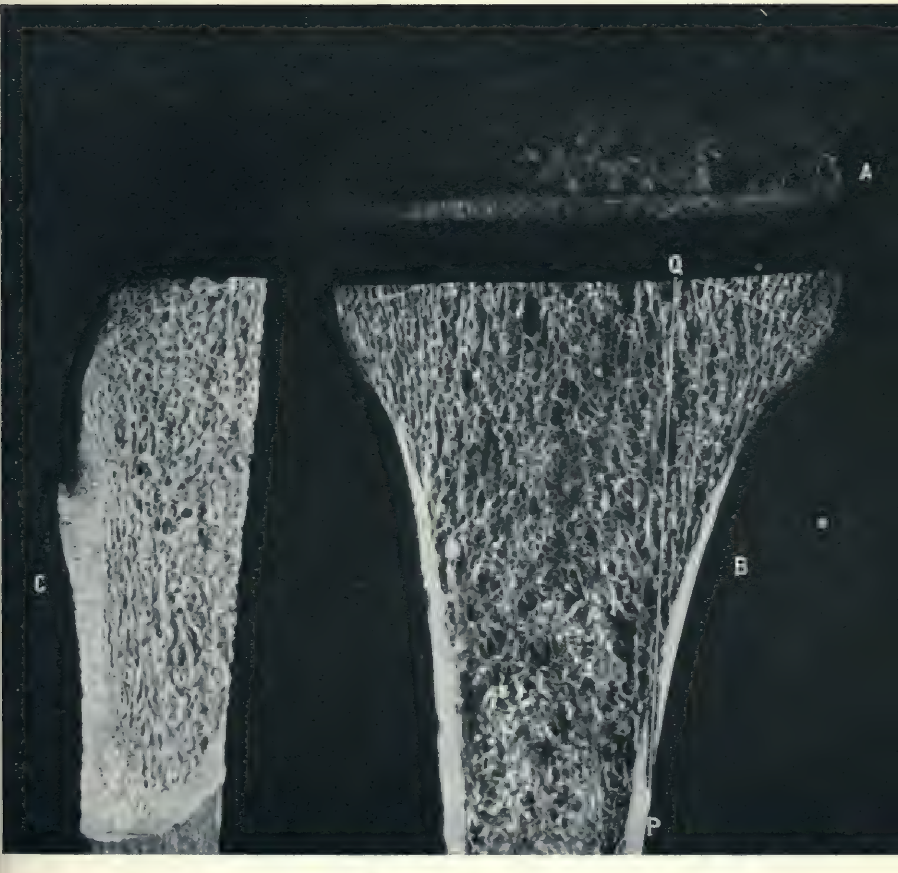


Fig. 42

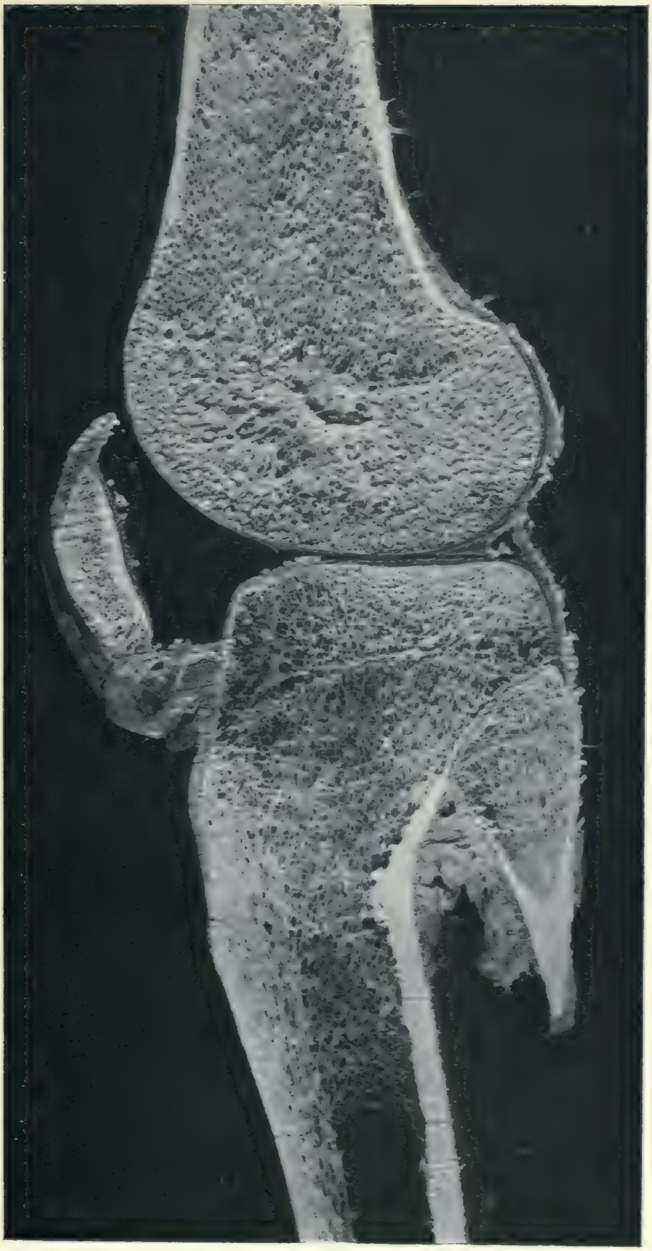
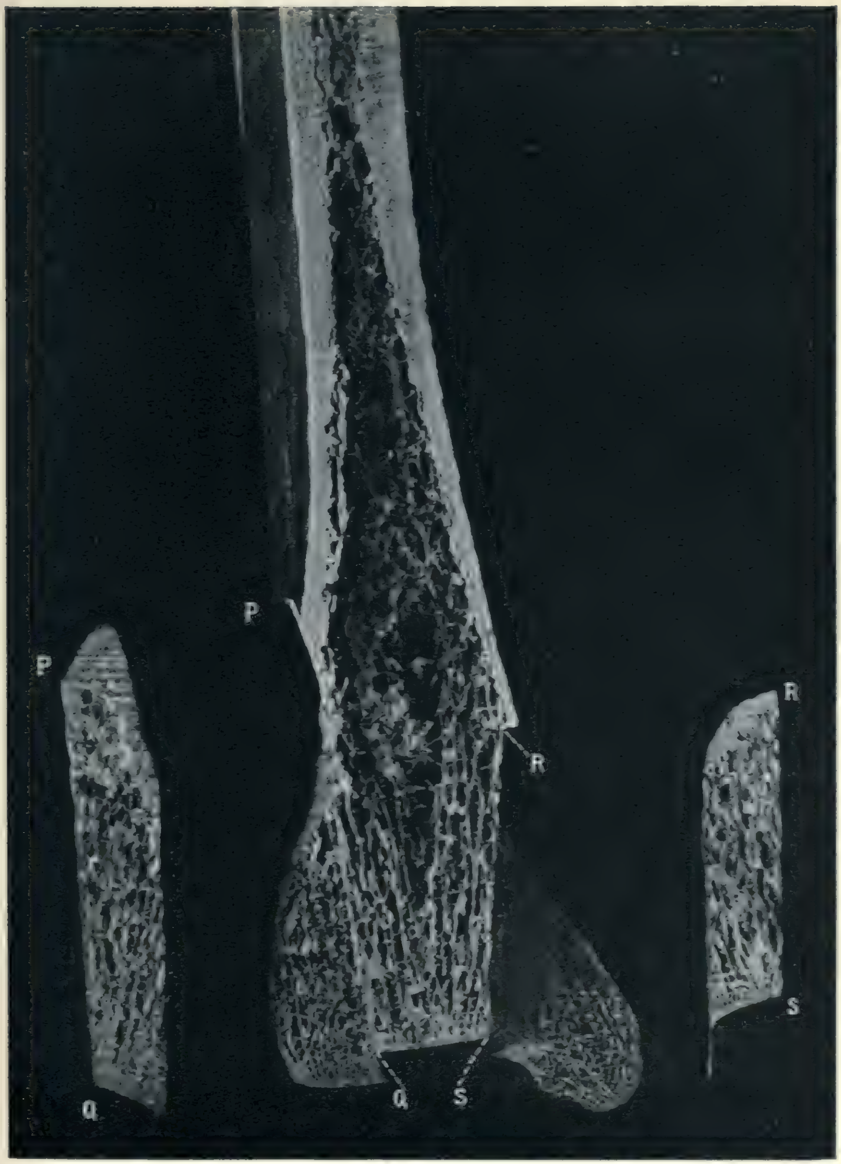


Fig. 43

The same difference is patent in Fig. 42, in which B represents the posterior half of the tibia and C the anterior half turned through 90°, and photographed after part of it had been sawn off according to an antero-posterior plane ending in the lines *PQ* (Fig. 42B). However, the contrast between the sagittal and the frontal section is far less marked here than in the *convex* side of the knee joint. The antero-posterior bone plates appear to be less complete, they show larger holes than in the lower femoral end (see Fig. 43). And this difference in structure answers to a difference in functional stresses. In the lower extremity of the femur the point which transmits the pressure to the tibia is a different one for every one of the numerous flexion positions. During flexion therefore the lines of stress in it radiate from a different point in each different position. Thus the number of lines of stress is great as well as the number of crossings. In the upper part of the tibia, on the contrary, the pressure acts on about the same point in the various positions of flexion. The number of lines of stress issuing from the surface therefore is much smaller as well as the number of their mutual crossings. Hence *in the concave side of the articular ends the number of bone trabeculæ required in the direction of the lines of stress is smaller than in the convex side, as well as the number of the mutual crossings of these bone strips*. And it is in accordance with this difference that the plates on the concave side of monaxial joints show larger apertures than those on the convex side. Nevertheless, they show evident preference for the plane of the chief pressure stresses.

The same rule holds good for the cancellous tissue of *all monaxial joints*. Compare the concave with the convex side of the sagittal section of the astragalo-tibial joint (Fig. 7), in which, as in the knee, the convex side appears to be of denser texture than the concave. And that all the same in the latter the bone elements show a predilection for the antero-posterior direction, is evident in Fig. 44b, two superimposed sections of the lower end of the tibia. From the anterior section two lateral parts have been removed by saw cuts made in the direction of the longitudinal elements and have been photographed on either side of Fig. 44b, after having been turned through an angle of 90°. These sagittal sections a and c, have a denser texture than the frontal ones (b). They show the antero-posterior bone plates seen from the side. The relatively large holes in these plates indeed cause the contrast with the frontal section to be less marked. Yet the transverse elements which form a striking feature in the frontal section of the lower end of the tibia (Fig. 44b), and which appear to unite the cribriform bone plates, remove all doubt that we are here, as in the articular ends of the knee, dealing with the characteristic picture of *monaxial rotation structure.*

From an anatomical side the objection has been made that we attribute too great a mechanical significance to the cancellous tissue of bones. Cancellous tissue, it was argued, has to harbour the bone marrow rather than to transmit pressure in all directions. With regard to the very thin and delicate bone trabeculæ inside the shaft of long bones (cf. the upper part of Fig. 44b), this view may be correct. However, it cannot be upheld with respect to the cancellous tissue in the articular ends which are now under discussion. The transverse section through the cancellous tissue in the widened articular ends, through the femoral condyles, for instance (see Fig. 37), or through the tibial condyles (see Fig. 46), strike cancellous tissue only. The cortex in them is indeed an extremely thin layer of bone which hardly surpasses the bone plates in thickness. Hence it is beyond doubt that the entire pressure of muscle action and gravitation in the epiphyses



a b c

Fig. 44

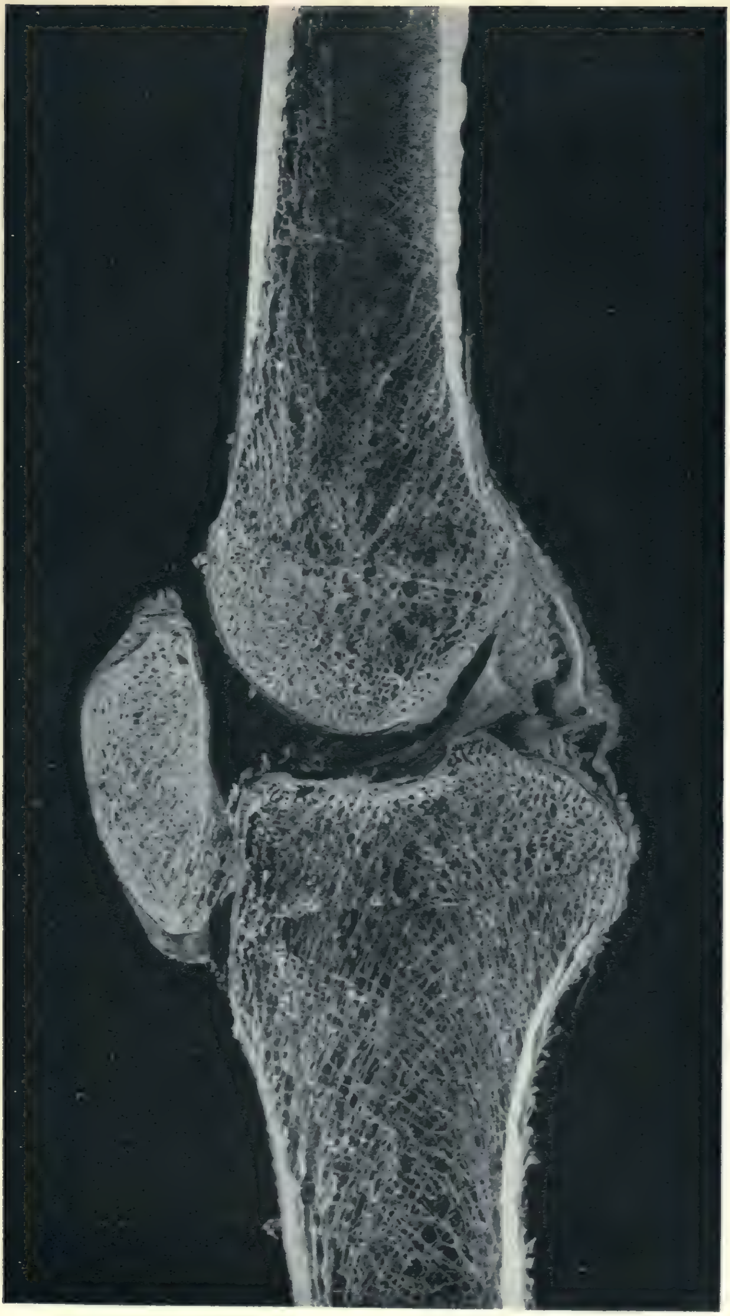


Fig. 45

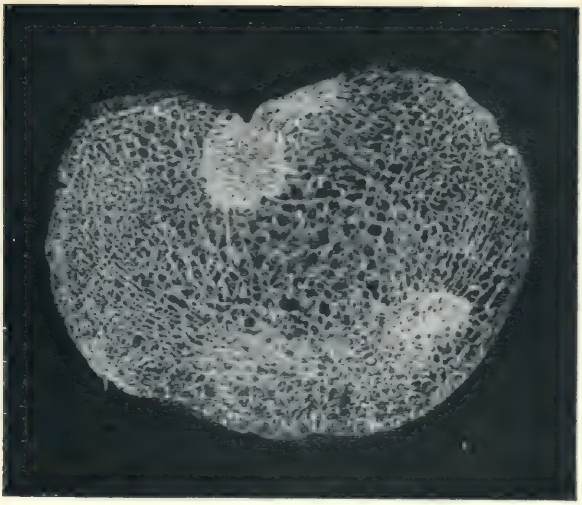


Fig. 46

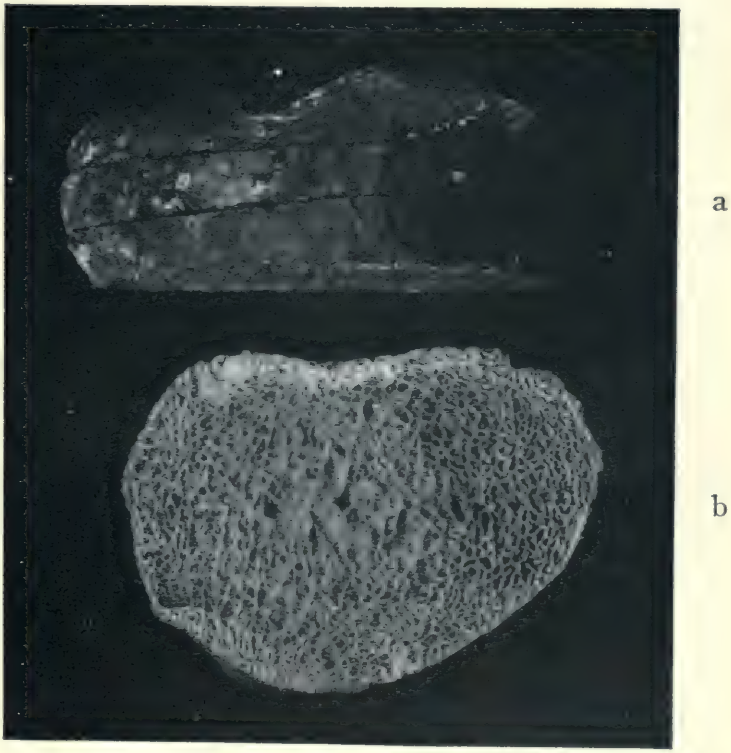


Fig. 47

is transmitted by cancellous tissue just as it is transmitted by compact tissue in transverse sections made through the diaphysis, whilst in the metaphysis the pressure stresses are borne partly by cancellous, partly by compact bone tissue. Indeed, the fact that cancellous tissue in articular ends will atrophy and even disappear on cessation of mechanical function (see Figs. 16—20 and Figs. 33—35), affords another proof for its intimate connection with such function. In the following pages this connection will be studied more closely.

In a sagittal section of the knee joint made between the femoral and tibial condyles (see Fig. 45), where the cancellous tissue has little or nothing to do with the task of transmitting pressure to the tibia, its structure is entirely different. Between these condyles we find the texture to be far less dense (see Fig. 45). The bone plates are missing. Only in the lower end of the femur a suspicion of them is visible. They are more developed in front than at the back, for which the pressure of the patella may be made responsible. For the rest the bone trabeculæ in these articular ends appear to diverge from the articular surface partly to the nearest cortex, partly to that of the opposite side (cf. the tibia of Figs. 36 and 45). The various crossings of these trabeculæ thus cause in the medial knee section figures to occur, suggesting Gothic arches which have their top directed to the articular surface. And, by the way, it may be noted that—in spite of the "discovery of orthogonality"—these arches form obtuse and sharp angles. It may be supposed that those bone elements which pass from one cortex to the opposite side, are brought about by all forces which tend to modify the angle in which the articular surface and the diaphyseal wall meet. A force, for instance, which lessens the angle at the back, will transmit pressure through the bone trabeculæ running from below and behind, upward and forward.

The reverse holds good for bone elements running from above and behind down to the anterior aspect of the diaphysis.

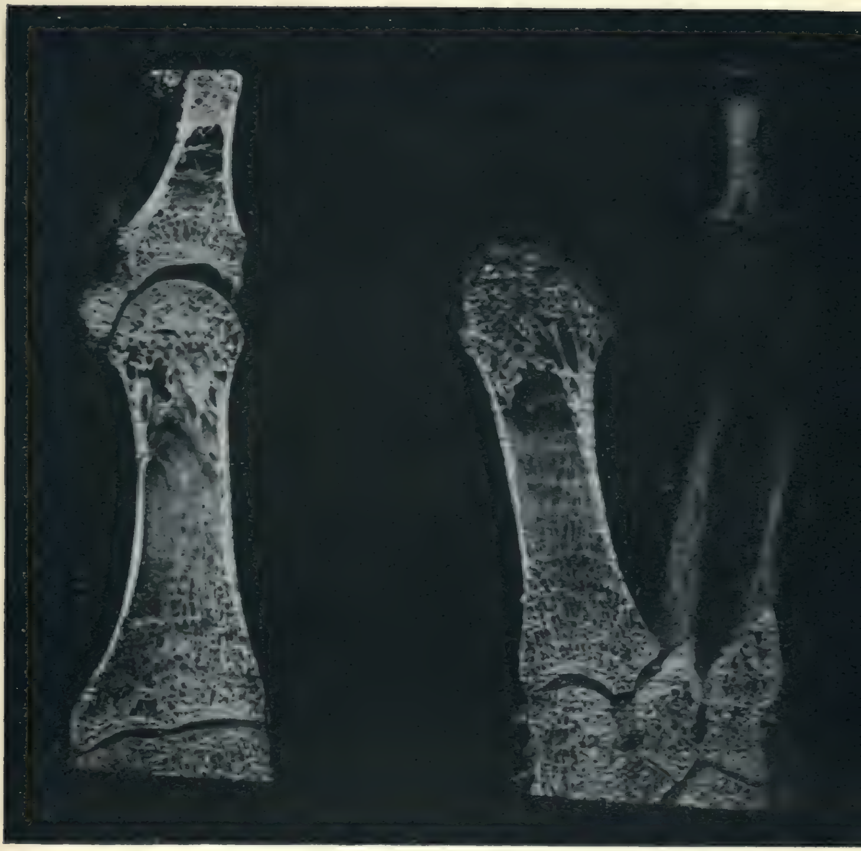
Between the concave and the convex side of a monaxial rotation structure, so to speak, fits in the *simple support structure,* in which a predilection of the bone elements for a special plane is lacking. We observe it *in the proximity of flat joint surfaces,* in its purest form near the end surfaces of *vertebral bodies.* In a section parallel to and very near these end surfaces (Fig. 26A), the vertical elements, *i.e.,* the elements of primary support, appear to be connected by transverse elements in all directions, so much so that one doubts whether they are preponderant in directions parallel to the circumference or in radial directions at right angles to it. Nearer the middle of the vertebral body (Fig. 26C) the radial direction of the transverse elements is preponderant. These radial bone elements have transmitted pressure forces running obliquely (cf. p. 41), as well as those directed transversely (due to the small bendings of the lateral surface of the vertebra), both of which are produced by bendings of the spine.

The thickening which the transverse elements invariably show at their extremities, rounds the holes which are left between the vertical and the transverse elements, and gives an impression as if the whole of the cancellous tissue were composed of tubes. *The close proximity of the relatively plane upper surface of the tibia* also approaches this support structure. This is shown by Fig. 46, representing a section made about ½ cm. below the articular surface of the upper end of the tibia, viz., the lower surface of the upper disc of Fig. 47a. A preference for the antero-posterior direction is hardly noticeable in this section, least so in the middle (cf. Fig. 45). With ALBERT, one might be tempted to speak of "contour-lamellæ." Only at some distance from the flat upper surface, the preference of the bone elements for the antero-posterior direction becomes visible (cf. Fig. 47b). In this we see a certain resemblance with Fig. 26c, in which also, only at some distance from the flat end surface, a preference of the bone elements for a definite—*in casu* the radial—direction is noticeable.

In the biaxial articulations two systems of lamellæ might be expected on the convex side, each corresponding more or less with the direction of the acting forces. However, in as much as movements are carried out in directions between these two planes, no such preference of the bone elements for the two chief planes of movement can be expected. Fig. 48a gives in the metatarso-phalangeal joint a picture resembling the monaxial rotation structure seen from the side. It is a dorso-planter section *through the axis of the first metatarsal bone* of the right foot. Fig. 48b is (of the left foot) a section at right angles to the former, *i.e.*, parallel to the sole of the foot. A comparison of the two at once shows the predilection of the bone elements for a confluence in a dorso-plantar direction: but the regularity in the parallel course of the bone plates which characterises the monaxial rotation structure, appears to be lacking here. A suspicion of plates running in other planes is noticeable here in which a share cannot be denied to the action of abducting and adducting muscles at right angles to that of flexion and extension forces. That nevertheless, the dorso-plantar system by far outweighs the bilateral one, is in conformity with the fact that during life the power and the effect of the flexion and extension forces greatly exceeds that of the abduction and adduction forces.

A similar preference for the plane of the most forcible movements we also observe in Fig. 49, the *lower end of the radius*. That, too, is a biaxial articular extremity—although a concave one—in which the formation of plates also preponderates in the plane of flexion and extensio forces. However, near the styloid process (at the righ hand side of the figure), this preference of the bone element for the plane of flexion and extension is absent. It mus be borne in mind that the movements between the tw principal planes are produced by muscles in the immediat proximity of the styloid process. There it is that the tw long extensors and the flexor of the carpus as well as th muscles for movements of the thumb—extensor oss metacarpi pollicis, extensor longus, and extensor brev pollicis, as well as the long flexor—pass over the bon Hence, in this very part of the radius, the muscular stresse are sure to run in all possible directions. So here, as i previous cases, a parallelism between the structure of th bone and the course of pressure stresses is patent.

If it may thus be considered an established fact tha in biaxial articular extremities the rotation lamella characteristic of monaxial articular extremities, disappea wheresoever the movements take place in a larger numb of planes, we find in the structure of such biaxial articul extremities a transition to the *triaxial joints*, in whic movements take place in all possible planes. The tran verse section of the *femoral head* for instance has a hom geneous spongy aspect. In the hemispherical end th bone elements start equally in all directions from th joint surface, and the apertures left between them a rounded equally in all directions. The section alon the axis of these bones shows distinctly how here, as i all previous cases, the elements are running in the directio of the acting pressure forces. We see them start fro the joint surface, meet (and cross, Fig. 1) in the midd of the head and pass on to the compact substance of th opposite side, and blend with it. And this does not app to the *frontal section* of the upper femoral extremity onl We observe the same structure—though less marked-



a b

Fig. 48

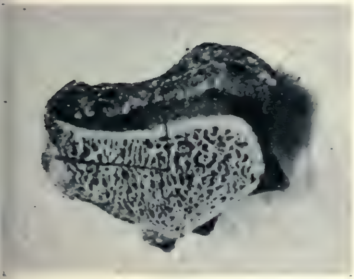


Fig. 49

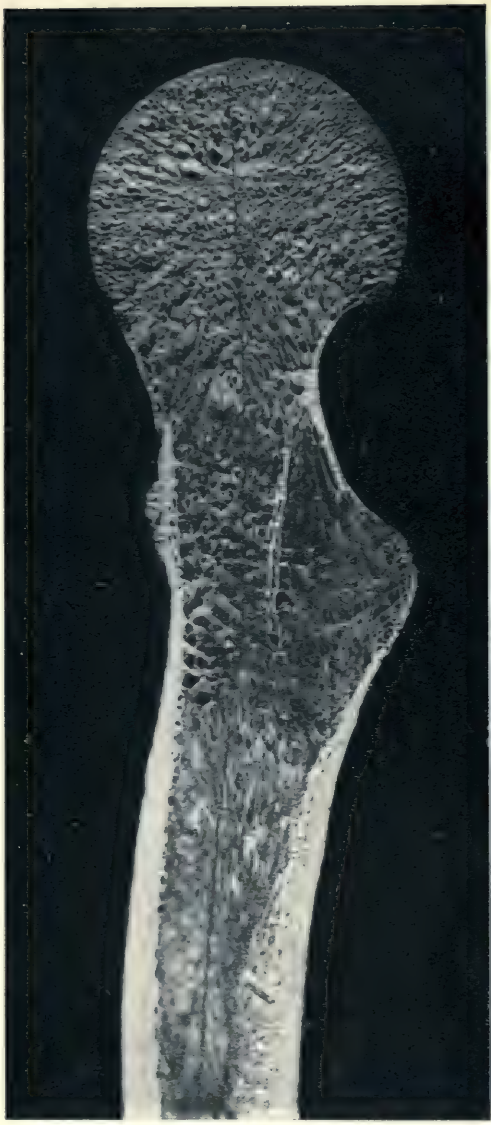


Fig. 50

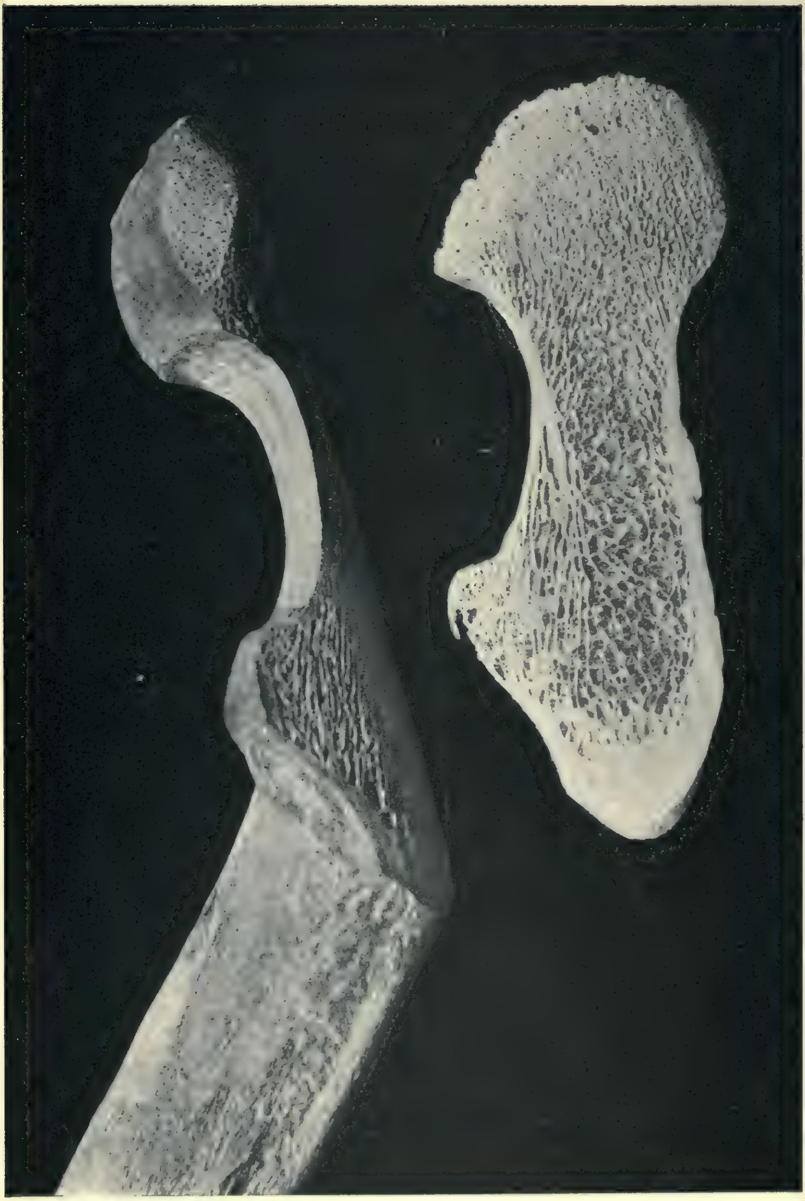


Fig. 51

in the *antero-posterior section of the femoral neck.* See Fig. 50, which is the lateral half of the same femur, the frontal half of which is represented by Fig. 5. Hence the plane of this figure is curved according to the saw cut along the axis visible in Fig. 5. This is less obvious in Fig. 51b, a disc which has been sawn off from Fig. 51a along planes bent in an antero-posterior direction, and the lateral surface of which has been photographed after having been turned through an angle of 90°. Yet even here it cannot be excluded with certainty that the bone elements start from the joint surface, meet in the middle of the dense cancellous tissue, and detach themselves from it in order to blend with the cortex of the opposite side of the femoral neck. These elements and their intersections may be less evident than those in the frontal section of the femoral neck, so that their existence might be questioned, but nobody will think of attributing any one of them to the action of tension stresses.

It may be of morphological importance to note that postero-anterior and antero-posterior elements blend with the cortex high up in the femoral neck (see Fig. 51b), just as the elements of the concave side of the frontal section in Fig. 1. The elements of the convex side pass into the compact cortex only at a greater distance from the femoral head, and have more or less the aspect of "contour lamellæ," which meet the cortex at regular distances (cf. Fig. 51b and Fig. 1), each having a share in its thickening. Or conversely, the compact cortex of the diaphysis of the femur may be considered to split up into cancellous elements which more or less retain the form of thin layers. The steadiness of these lamellæ is secured by multiple mutual connections. That the analysis of the forces which lead to the blending of the bone elements into these lamellæ meets with difficulties, needs no comment. Nevertheless it may be considered an established fact that in the area of these "contour lamellæ" pressure stresses are transmitted during life which cross in many directions.

Fig. 51B also shows the bone plate which MERKEL has called the "femoral spur" and which 30 years previously had been described by RODET as "lame osseuse sous-trochantérienne" *viz.*, the continuation of the diaphyseal wall which is, so to speak, placed inside the bone by the development of the lesser trochanter.[1] Possibly it is to be considered as an analogy to the continuation of the diaphyseal wall through cancellous tissue, as is shown in Fig. 33.

In the concave side of triaxial joints the divergence of the bone elements is a striking feature, just as in that of the bi- and monaxial joints. These elements are, so to speak, the continuation of those crossing in the convex side. The forces to whose action the transverse elements in the *concave side of the hip-joint, i.e.*, in the acetabulum (cf. Fig. 1), are to be attributed, can be stated with less accuracy on account of the complicated form of the pelvis and the large number of forces to which it is submitted. Yet, it must be emphasised that pressure stresses cannot be excluded any more in these transverse elements than in those of other bones (cf. p. 20). So they cannot be considered as a product of tension stresses.

If we survey what the above study has taught us, it appears that *the structure of cancellous tissue can be largely understood, if we consider it to be composed of bone elements coinciding with pressure stresses* caused directly by muscle action and body weight.

These bone elements (*primary elements*) show slight undulations in their course. They split up or blend together, and are in many places united by short oblique and transverse elements (*secondary elements*).

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[1] Cf. POIRIER, Anatomie 1899. Tome I., p. 230.

Wherever the lines of pressure stresses cross in many points of the same plane, the (primary) bone elements fuse into bone plates or lamellæ in which small circular holes are left close to the joint surface, and larger more oval holes at some distance from the surface. The mutual connection and stability of these plates is insured by secondary bone spicules (*monaxial rotation structure*). The more numerous the intersections of the lines of stress are, the more complete are the plates, *i.e.*, the smaller the remaining holes. Hence the plates or lamellæ on the concave side of monaxial rotation structures are more complete than those on the convex side.

Wherever the lines of pressure stress cross in more than one place, the lamellar structure is departed from in proportion as the number of planes of movement increases (*biaxial and triaxial rotation structures*.) Near the head of triaxial joints we see the compact bone dissolve into mutually-connected bone elements which, coming from all directions, meet in the middle of the articular head, where they cross in order to end at right angles to the articular surface.

Wherever pressure is displaced by tension, be it in the direction of the primary elements, or in that of the secondary ones, we see atrophy of the cancellous tissue.

Wherever the articular surface disappears as in ankylosed joints, and *the pressure stresses pass through a smaller transverse section, cancellous tissue approaches the structure of compact bone.* Conversely, *compact bone passes into cancellous tissue on an enlargement of the transverse area transmitting the pressure stresses.*

Nowhere in cancellous tissue did we meet with bone elements in which the action merely of tension stresses had to be assumed.

These are, in short, the rules according to which the formation of cancellous tissue takes place, in as much as it is determined by pressure stresses. They are applicable to deformed bones as well as to normal ones. With a modification of the direction of the pressure stresses in cancellous tissue, the direction of the bone elements will be modified, for which phenomenon WOLFF'S name " transformation " may be preserved, although his " law " of transformation has to be abandoned for reasons exposed in Chapters II and III.

The above rules given for the formation and the transformation of cancellous tissue do not claim completeness. Nor was this the aim of the present research, which was only intended to prove that a *monistic explanation—exclusively by pressure—of the structure of cancellous tissue is possible*, be it only very roughly, *without meeting with difficulties which make the dualistic explanation—by pressure and tension—untenable.*

In the following chapter we will try to study more closely the nature of the pressure which has a formative effect on bone.

CHAPTER V.

NATURE OF THE PRESSURE WHICH FORMS BONE.

If we have demonstrated in the previous chapters that the existence of cancellous tissue depends on the action of pressure stresses to such an extent that its structure is largely determined by them, yet a number of facts seem to be in absolute contradiction to this assumption.

In 1862 VOLKMANN[1] directed attention to the fact that bone tissue shows a " tendency to yield (" Nachgiebigkeit ") to the slow continuous pressure " of Pacchionian granulations, growths arising from the dura mater, aneurisms or articular heads.

It should be noted that grooves dug by Pacchionian granulations, growths arising from the dura mater, arteries and aneurisms, must not be identified with the deformation of articular ends. In both cases bone gives way to pressure; but the deformation of articular heads is accompanied by broadening and lipping of the bony edges. This suggests the assumption of a certain plasticity of the bone substance, whereas there is no displacement whatever of bone near the grooves for Pacchionian granulations and arteries. For this reason, and another which may become patent in this chapter, we shall easily distinguish the two phenomena. The apparition of grooves for arteries will be termed " yielding," and due to a " tendency to yield " ;

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[1] R. VOLKMANN, Chir. Erfahrungen über Knochenverbiegungen und Knochenwachstum, VIRCHOW'S Archiv. Bd. XXIV, 1862, p. 521.

the flattening out of articular ends, "plasticity" of bone tissue. Only the former will be dealt with in this chapter; for the latter we may refer to the following chapter.

In 1883 KORTEWEG[1] also emphasised this "property." "Bone is deformed more easily by the surrounding soft parts: muscles, tendons and blood vessels dig noticeable grooves into bone, whilst the reverse never takes place, so that impressions made by bone in softer tissues are never observed. . . . If, for instance, we consider a tibia," KORTEWEG continues, "we find the anterior surface convex, moulded by the skin and the underlying fibrous tissue, whilst the outer and posterior aspect show concave surfaces, which have accommodated themselves to the pressure of contiguous muscles." In perfect agreement with these observations, ZSCHOKKE found a perforating hole in the nasal bone of a horse which had gradually been developed by the pressure of the head stall.

For the explanation of this demolition of bone, *hypotheses* have been raised from various sides. VOLKMANN assumed the cause to lie in the "slow and continuous" action of the pressure. KORTEWEG is of opinion that the evenness of the pressure is the cause: constant pressure, he says, will destroy bone, intermittent pressure will form bone. This contrast in effect between constant and intermittent pressure is, according to him, brought about in consequence of the fact that intermittent pressure causes an accelerated flow of the tissue liquids by way of an internal massage. Whether indeed such slight variations in volume of the blood and lymph vessels as are caused in bone tissue by the intermittence of pressure, have an accelerating effect on the contents of these vessels, is a theoretical problem which we must leave unsolved for the present. Certain it is that the accelerating effect of intermittent pressure on the flow of liquid in vessels (in bone tissue) demands the presence of valves in these vessels. KORTEWEG does not mention this. According to POIRIER[1] such valves do not occur either in the veins of the bone marrow or those of the compact bone tissue, but only in those of the periosteum. And if appreciable changes in the size of the vessel are brought about by intermittence of pressure, it cannot be denied that these valves may accelerate the flow of the nutritive fluids. However, facts seem to be in contradiction with the assumption that this difference between constant and intermittent pressure should solely determine the difference in behaviour of bone tissue: *the pressure of the muscles,* for instance, which determine the excavation in the lateral surfaces of the tibia, cannot be called a purely constant pressure; and the same holds good—possibly even in a higher degree—for *the pressure of pulsating arteries* which dig grooves in bone.

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[1] J. A. KORTEWEG, Nederl. Tijdschrift voor Geneeskunde, 1883.

HIRSCH,[2] who altogether denies the effect of muscles on the form of bones, discusses the impression of a dermoid cyst in the skull, and assumes that, as long as the pressing force is small, for instance, a few grammes per square mm., and acts on a part not prepared to bear pressure, the compression of the periosteum is the cause of the disappearance of bone tissue. Even though the pressure of a dermoid cyst may be assumed to be small, it is *not* on that account *admissible that on an increase of that pressure the* (periosteal) *bone would offer resistance and be maintained.* Moreover, HIRSCH fails to explain of what the "preparedness of bone to resist pressure" consists.

MÜLLER,[3] in Stuttgart, assumes the cause to be in the cartilage. Where this is present, he considers it to act like a buffer. HIRSCH raises the objection that a dermoid cyst surely does not act less as a buffer than cartilage.

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[1] POIRIER, Anatomie T. I, p. 109.

[2] Centralblatt f. Chirurgie, 1896. N. 25, p. 595.

[3] Quoted from HIRSCH, l.c.

And we may add that, if indeed the buffer action of cartilage as such should enable the long bones to bear the pressure of body weight and muscle action without deformity, the slight pressure of the covering parts transmitted to bone by a dermoid cyst, ought to be borne all the better without deformity of the bone.

An aneurism of the aorta, which excavates the anterior and lateral surfaces of the vertebral bodies, throws some more light on the relations between pressure on the one hand and bone formation or resorption on the other; the dilatation of the aorta is the apparent result of the fact that the arterial wall is too feeble to bear the whole of the blood pressure. So part of this pressure is transmitted to the surrounding tissues, viz., the vertebral bodies. In warm-blooded animals the average blood pressure in the aorta measures about 200 mm. Hg., *i.e.*, about ¼ Kg. per cm. So an aneurism of the abdominal aorta which excavates the anterior and lateral surfaces of the vertebræ, would bear on it a weight of ¼ Kg. per square cm, if the whole of the blood pressure should be transmitted to it. The aortic wall, however, always bears part of the blood pressure itself (at least as long as it does not burst). Hence the pressure which excavates the lateral surface of the vertebral bodies amounts to less than ¼ Kg. per square cm. The horizontal section made through the middle of one of the lowest lumbar vertebræ, measures about 15 square cm. As this is not situated far from the centre of gravity of the body, we may assume that in the erect attitude half the body weight is borne by it, *i.e.*, ± 30 Kg. or ± 2 Kg. per square cm. Consequently, *two Kg. of pressure per square cm. are easily borne by vertebral bodies in the direction of pressure for which the bone is built, but a pressure which amounts to about one-eighth of this, acting at right angles to the normal pressure, leads to a rapid demolition of bone tissue, although it is, like the normal pressure* (of body weight and muscle action), *of an intermittent*—or better, remittent—*character*. This suggests that bone is, so to speak, defenceless against lateral pressure. So destructive at any rate is the action of the pressure of the aneurism on bone tissue that even the trophic stimulus of the normal body weight and muscle action which acts at the same time, is unable to prevent it from destruction. Hence, *in bone tissue we observe a natural liability to absorption, a tendency to yield, with regard to the lateral pressure of the softer neighbouring tissues.* It allows itself to be rounded by fasciæ, grooved by vessels, excavated by cysts; it gives way to tumours even in the interior of cancellous tissue, and last, but not least, gives way to the pressure of the aneurism of the aorta to such an extent that its function is locally abolished.

The tendency of bone tissue to yield to the lateral pressure of softer parts is a useful quality inasmuch as it forestalls the evil effects these parts might otherwise sustain from close contact with prominent surfaces of the bony material. In cases of aneurism of the aorta, as dealt with in the above, however, it becomes disastrous, the bone substance proving to be more sensitive to the gentle lateral pressure of the flexible parts than to the much stronger functional stresses which, in an axial direction, stimulate its formation. And the yielding to lateral pressure has been so deeply inculcated on the bone substance that JÖSSEL found a groove in a radius answering to a tendon which failed congenitally. Hence the bone cells seem to know their obligations to the tissues surrounding them in normal conditions, and the question arises: *Does only the direction of the pressure with regard to that for which bone is built, play a part, or also the nature of the pressure?*

It is not to every pressure which acts laterally that bone tissue gives way. Even ZSCHOKKE admits that prominences develop on bone against a lateral pressure of muscles. So, for instance, the trochanter minor arises on the femur where the iliopsoas muscle winds round its internal side. Similarly, the tuberosity of the radius with regard to the tendon of the M. biceps brachii. So here bone tissue develops in the direction of the lateral pressure, instead of disappearing from it. And the sesamoid bones, which develop in places where the tendons form an angle bending round the bones (patella and pisiform), differ from these prominences really only in that they are connected with the tendon instead of being connected with the bone. Hence, if on the one hand we see bone tissue give way to tendons which run parallel to the direction for which it is built, on the other hand we see it develop wherever the tendons bend around it and thus send part of the pressure of muscle action through the bone tissue. We did see in the previous chapter that the pressure of muscle action and gravitation, roughly speaking, determines and maintains the structure of cancellous tissue and compact bone in bones of the extremities and in vertebral bodies. We now see that this pressure, even if it acts in a lateral direction, has a formative effect on bone in contrast with pulsating arteries and other soft parts (acting in the same direction). We see, in other words, that *as soon as side pressure adopts the character of muscle function, bone tissue is formed in the direction of the pressure, either detached from the bone—in the form of bones lying in the tendons* (*sesamoid bones*)*—or connected with the bone—in the form of prominences* (*tuberosities, trochanters*). *The jerking pressure of muscles in connection with that of gravity appears to be the mechanical stimulus which promotes bone formation*—at least in the bones of the extremities and the vertebral bodies.

Not only on the form but also on the size of bones the jerking pressure of muscle action and gravity seems to have an effect. At least we observe an unmistakeable parallelism between the intensity of that pressure and the length of the extremities and their parts both in animals and in man. Only in animals living on land the jerking pressure of muscle action and gravity makes itself felt in the development of the extremities. From the reptiles to the mammalians the extremities are gradually placed more and more in the direction of gravity. At the same time their length gradually increases, whereas in the aquatic mammalians they are reduced again to finlike appendages. In man, in whom the posterior extremities exclusively serve for locomotion we see them, according to the higher exigencies they have to meet, reach a higher degree of development than in quadrupeds, whilst at the same time the length of the phalanges, decreasing in a distal direction, seems to be in harmony with the decreasing power of the pressure stresses of the tendons decreasing in number accordingly. However, there is no doubt but that in these complex relations factors other than mechanical play a part. Nobody, for instance, will think of ascribing the exceeding length of the legs of wading birds, with regard to those of swimming birds, to the mere effect of the jerking pressure of muscle action and gravity; or the excessive length of the neck of the giraffe to greater pressure of neck muscles, and the greater length of its fore legs compared with its hind legs, to the greater weight which they have to bear on account of the extreme development of the neck.

The jerking pressure of muscle action and gravity, however, is not the only pressure with which the development of bones runs parallel. In aquatic mammals the ribs are wide, either round or square in their transverse section and consisting largely of compact bone, whilst in terrestrial mammals they are thin and have a flat transverse section, which largely consists of cancellous tissue. So here *a parallelism seems to exist between the difference in pressure outside and inside the chest* on the one hand and bone formation on the other. A similar parallelism may possibly be assumed in the strong development of the products of the first branchial arch (maxilla and mandible), in contrast with that of the three lower ones and the greater pressure stresses to which it is exposed during movements of mastication. Be this as it may certain it is that not in the jerking pressure of muscle action and gravity as such, but rather in the *pressure of function, functional pressure, the stimulus for bone formation in the various skeletal parts, is to be traced.* Not the intermittence or remittence in action of the pressure as such, but functional pressure seems to be the specific mechanical stimulus for bone formation, so that we may with ROUX speak of the *trophic stimulus of function* (although we differ with him in denying such a stimulus to tension stresses). And this specific sensibility of bone cells is comparable to that of the retina cells with regard to light, of the auditory organs with regard to sound. To any other pressure we see bone give way, at least when the pressure acts at right angles to the direction for which it is built. The question arises: will such pressure—*i.e., a non-functional one—acting in the direction for which bone is built, equally lead to waste of its substance?* We cannot exclude this possibility with certainty, but tend to assume that this is not the case; hence that in the direction for which bone is built any other non-functional pressure, be it constant or remittent, is withstood better than in directions at right angles to it.

The following facts favour this assumption:

After WOLFF had taught in his "Law of the transformation of bones" that both the external form and the internal structure of bones were entirely and exclusively determined by the external forces which act upon them, and had thus represented bone tissue as a material completely plastic with regard to external forces, attempts have been made to straighten curved bones by constant pressure acting upon the top of the curve—and in an opposite direction—upon its ends. Now in full-grown bones (*i.e.*, in bones in which a modification of growth in the epiphyseal cartilages by such a modification of pressure may be excluded) this treatment regularly leads to disappointment—except in very flexible highly abnormal bones. And even in young bones decubitus of the soft parts will be oftener seen and possibly also demolition of bone at the site of direct pressure will sooner be observed, than a straightening of the bones. Yet in such cases the constant pressure also makes itself felt in the longitudinal direction of the bone. Hence *bones seem to have the power of resisting constant pressure in their longitudinal direction better than in the direction at right angles to it.*

If the difference in sensibility of bone tissue to the direction for which it is built on the one hand, and to the directions at right angles to it on the other, may be considered as an established fact, the arrangement of the cells in the bone tissue obtains special significance.

In previous pages we directed attention to the fact (see p. 60) that the bone cells, whose form—apart from the protrusions—may be compared to melon seeds, are upon the whole situated in such a way that their longitudinal axis coincides with the direction of the pressure which the bone tissue has to resist. In compact tissue furthermore the transverse dimension corresponds with the circumference of the Haversian lamellæ, and with the direction of the basal lamellæ, so that a pressure from the side—for instance, at right angles to the axis of a diaphysis—which reaches the bone cells, upon the whole coincides with the direction of the smallest dimension—the width—of the bone cells in contrast with functional pressure in the direction of the diaphyseal axis, which largely coincides with the greatest dimension—the length—of the bone cells. In the plates of cancellous tissue we also see the bone cells situated with their lateral surfaces in the plane of the plates, whilst their longitudinal axis, in conformity with the numerous directions of pressure is arranged in lines crossing each other. *Hence the bone cells seem sooner to give way to pressure acting on their largest surface, i.e.*, in the direction of their smaller dimensions *than to pressure acting in their longitudinal direction.* In other words, with respect to this lateral pressure bone cells seem comparable to troops whose flank is attacked, or to a shoal of fish, which can easily meet the pressure of a strong current as long as their longitudinal axis coincides with the current, but which would be unable to offer resistance if the current should act on the lateral surface of their body.

But whether bone cells can resist pressure in their transverse dimensions as well as in their longitudinal dimensions or not, certain it is that bone tissue in its tendency to yield to the softer sister tissues of its surroundings shows the art of living with them without disturbing them in their structure and function. Thus bone tissue in the microcosmos sets an example to the individuals in the macrocosmos with regard to the manner in which a co-operation for a common higher purpose becomes possible.

The tendency of bone to yield to sister tissues—or whatever the giving way to pressure of contiguous softer parts may be called—throws some light on the conception according to which the very same soft pressure which causes such deepenings in bone, is considered at the same time to exert a trophic stimulus (cf. p. 28 to 30). Nobody indeed will think of earnestly asserting that the gentle side pressure of the widening aorta, which demolishes the vertebræ although functional stimuli are acting (in an axial direction), at the same time exerts a trophic stimulus on bone; or that the lateral pressure of contiguous muscles which excavates the tibia, would at the same time act as a stimulus to bone formation. In view of these facts (apart from other considerations (see Chapters II and III), can the gentle pressure of the contents of the skull which causes the impressiones digitatæ, Pacchionian grooves be earnestly considered at the same time to cause boneformation in the skull ?

CHAPTER VI.

QUANTITATIVE RELATIONS BETWEEN FUNCTIONAL PRESSURE AND BONEFORMATION.

If in the previous chapter the parallelism between functional pressure and boneformation has led us to assume that this pressure is a specific stimulus for bone formation, it will now be our task to trace to what extent this parallelism shows itself in those rare cases in which functional pressure rises or falls outside normal limits.

Little, indeed, is known with certainty of these relations. The considerations of this chapter, therefore, are not offered to the reader for the adoption as established truth so much as for criticism and completion.

Such rises of pressure as act suddenly, mostly only for a short moment, and lead to a solution of continuity, will be left out of consideration. Only rises of pressure of longer duration will be considered which cause bends or curves as in the neck or diaphysis of the femur—and flattenings or depressions, as in cases of incongruency of articular ends.

In the previous chapter we observed that R. VOLKMANN has directed attention to the deformation of articular ends (and has unjustly identified this deformation in the direction of functional pressure with that caused by pressure acting at right angles to functional pressure). If we assume, says VOLKMANN,[1] that the femoral head is pressed down by bodyweight and muscle-pull $\frac{1}{1000}$ of a second—a possibility which everybody will be ready to admit—the displacement will not be permanent, as long as the stresses in the femoral head counterbalance the external forces, *i.e.*, as long as the stresses in the femoral head which have been evoked by compression of the elastic bone tissue, are not diminished. However, the condition changes when these stresses are levelled by metabolism, when absorption of lime salts takes place in the parts rendered dense by compression—a process we have every reason to assume, and which may be termed interstitial absorption, a name also used by HUNTER, though in a different sense. Then besides the differences of stress being levelled, and the bone being fixed in its abnormal form, the pressing forces may act anew on the bone. It may be further compressed or bent. The deformation, the lowering of the head, may increase gradually and even *in infinitum*. Thus VOLKMANN advocated *primary absorption of lime salts and secondary plasticity ensuing from pressure on bone*—a process evincing *insufficiency of bone*. It is true, J. WOLFF, in his "Law of Transformation," afterwards asserted that the very reverse of VOLKMANN'S views was right, that the formation of bone was always proportional to pressure (and tension); but all clinical data favour VOLKMANN'S view. And we have arguments which cannot be brought forward at this place, favouring the assumption that in the development of deformities the insufficiency of bone plays a role that has been too often overlooked.

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[1] L.c., p. 520.

It stands to reason that in cases of abnormal flexibility of bone, progressive bendings and curves may be brought about by normal pressure (*absolute insufficiency of bone*), whereas in normal bone excessive pressure will be needed to provoke plasticity (*relative insufficiency of bone*).

An illustration of primary absorption of limesalts in normal bone to hypernormal pressure, may possibly be seen in the well-known fact that pegs driven into living bone, soon lead to absorption of lime salts round the peg and not at a distance from the peg. The pressure borne by the peg on the surrounding bone substance—and therefore, also, the compression of the bone tissue—is obviously inversely proportional to the square of the distance of the elements from the peg. Hence, there is a parallelism between the small extent of the area of excessive pressure and the smallness of the area of absorption of limesalts. Chemical factors, indeed, will have to be excluded to justify the assumption that it is the hypernormal pressure which leads to this primary absorption of limesalts in bone. Yet the phenomenon surely favours VOLKMANN'S view that excessive pressure, when causing no fracture, leads to primary absorption of lime salts and secondary deformation of bone, *i.e.*, secondary bending or compression (shortening and widening out) of the parts.

A diminution of lime salts seems equally to present itself whenever pressure remains *below* the normal. The greater translucency to X-rays which bone shows after subnormal weight bearing—for example, the medial condyles of femur in genu valgum—may favour this, for as much as the lighter shade such bone gives on röntgenograms, is not caused by thinness of the bone elements as such.

We, therefore, tend to assume that in cases of subnormal functional pressure on bone the quantity of limesalts lags behind the normal, and that in bone which is made to bear hypernormal pressure exceeding certain limits, the quantity of limesalts sinks below the normal. And if we are justified in doing so, it is evident that the plasticity of bone is enhanced whensoever functional pressure rises or falls outside normal limits.

In the book quoted in the preface of this treatise we have studied bone *growth*. In it we have directed attention to the fact that bone growth is normally split up into three stages, viz., (1) cell division, (2) cell enlargement, and (3) differentiation. In the third stage the deposition of limesalts takes place. These three processes are normally visible side by side in the growth cartilages where the cartilage cells develop, where they enlarge (columns of cartilage cells), and where they, on both sides of the vascular loops, change into (or make room for) bone cells. In the same study we have tried to prove that any injurious agent, provided it be serious enough, that befalls a growing individual, enfeebles its growth or causes dwarfism. Now the notable fact has presented itself that in all such cases of feebleness of growth or dwarfism the third stage, that of differentiation, is retarded more than the first two stages (of cell division and cell enlargement).

If, indeed, the limesalts decrease in *pre-formed* bone which is subjected either to subnormal or to hypernormal weight bearing, this is comparable to the retardation of differentiation constantly observed in *growing* bone which has been subjected to serious injurious influences. The rise and the fall of functional pressure outside the normal limits in *pre-formed* bone then are comparable to injurious agents which retard differentiation in *growing* bone ; and if the decrease of limesalts in pre-formed bone may be *identified* with the retardation of differentiation in growing bone, the general rule may be established that injurious influences evoke a retardation and retrogression of differentiation both in growing and in pre-formed bone.

In the treatise just quoted we have studied the longitudinal growth of bones—with regard to functional pressure—of normal skeletons and of those whose power of growth is enfeebled by injurious influences, and have tried to give a graphical representation of the facts they present. In it we obtained the curves of Fig. 52 by noting down functional pressure on the horizontal, growth on the vertical axis. In this figure, curve *I* represents the growth of the normal skeleton; *II* that of skeletons that have been slightly injured, *i.e.*, those showing slight feebleness of growth; *III* that of skeletons which have been seriously injured, *i.e.*, those showing serious feebleness of growth.

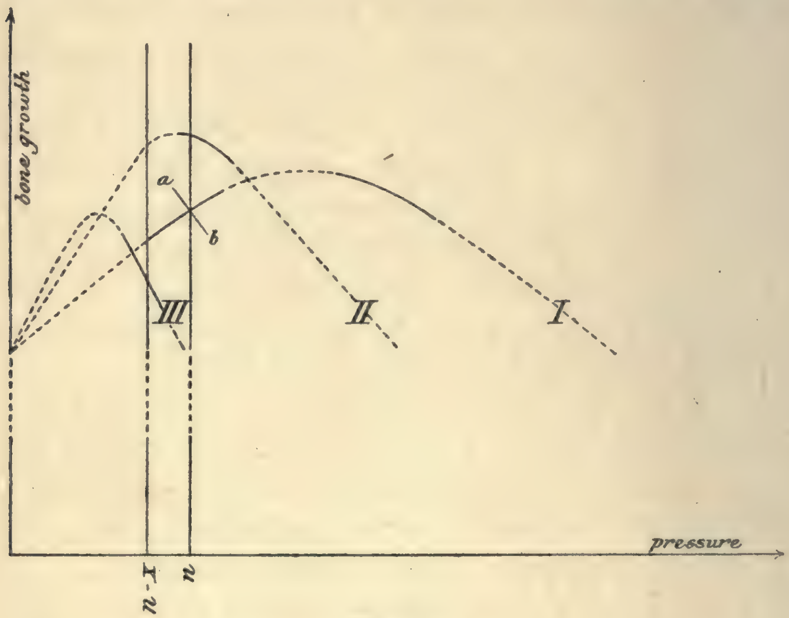

Fig. 52

Now it may be considered probable that, on the whole, these curves are also applicable to *pre-formed* bone in these skeletons: Bone formed during severe feebleness of growth has, as is well known, a shortage of lime salts, which may last for a longer or shorter period. Such bone is obviously more sensitive to functional pressure than normal bone. Therefore, if we may assume that on a constant increase of functional pressure the quantity of bone formed in normal bone diminishes after an optimum of pressure is exceeded, it is patent that in soft bone the descent of the curve begins at less pressure. In soft bone, moreover, the ascent of the curve will be steeper than in normal bone, as well as the descent.

So, if the quantity of bone formed in normal skeletal parts on a constant increase of functional pressure, is represented by curve *I* of Fig. 53—pressure being noted on the horizontal, the amount of bone formed on the vertical axis—there is no doubt that in soft bone the curve will fall sooner (for example as curve *II*, Fig. 53). And very soft bone will show a fall of the curve to still less pressure (as for example, curve *III*, Fig. 53). Enhanced softness of bone will, moreover, manifest itself under subnormal pressure by enhanced sensibility to pressure, *i.e.*, by a steeper rise of the curves, as is represented in Fig. 53. Hence we have reasons to assume that there is a similarity in the reaction to pressure in growing bone and in preformed bone. And it seems hardly risky to state that in bone affected by slight feebleness of growth, the formative effect of functional pressure may exceed the normal (as is expressed in the height of curve *II* of Fig. 53), whereas it seems bound to lag behind the normal in bone affected by serious feebleness of growth (as is laid down in the height to which curve *III* of Fig. 53 reaches). In

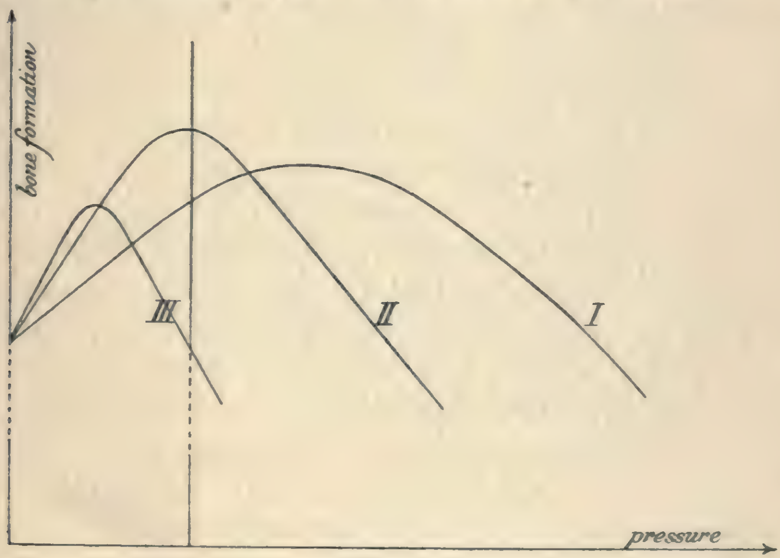

Fig. 53

other words, there are reasons favouring the hypothesis that the effects of functional pressure on bone—on normal bone as well as that affected by feebleness of growth—are largely the same both for its growth and its formation.

In Fig. 53 the descending part of the curves has been lengthened below the horizontal line from which they start in order to represent the fact that excessive pressure leads to compression, and possibly disappearance, of bone.

If we may assume that under subnormal as well as under hypernormal functional pressure, the lime salts are the first to disappear from bone tissue, Fig. 54 may give a graphical approximation of the behaviour of lime salts with regard to the other processes of boneformation.

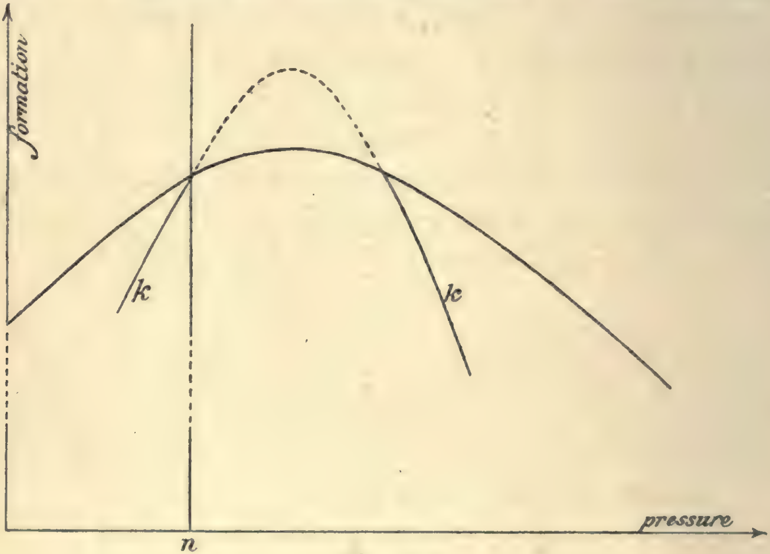

Fig. 54

In Fig. 54, the thin uninterrupted lines *k*, *k* then represent the behaviour of the limesalts, the thick uninterrupted line that of the other bone elements with regard to functional pressure. And if it may be assumed that the uninterrupted lines *k*, *k* are also parts of a physiological curve, they will have to be completed in a way not essentially different from the interrupted line uniting them in the Figure. Be this as it may, the interrupted line seems to show the well-known clinical fact that bone which is exposed to gradually increasing pressure, becomes harder than normal, " eburnates," at least as long as the pressure does not exceed certain limits.

It must be emphasized that the above curves are meant only as a vague approximation of clinical facts. They may be useful until careful measurements shall produce more accurate data. But even those who will be inclined to consider them useless, should not lose sight of the fact that bone under excessive functional pressure loses its vital power of resisting this pressure. It changes its stubborn, resistant nature, and assumes plasticity. And to us it will seem that till further notice the above curves may guide our considerations for preventing and treating the plasticity of bone tissue, sometimes also for evoking it for therapeutic purposes.

The plasticity of which the above deals, bears reference to deformation by functional pressure only. Bone tissue, moreover, shows plasticity with regard to twisting forces: the anteversion of the femoral neck, as we mentioned before, regularly increases in the later months of intra-uterine life of the human embryo, and decreases after birth. LE DAMANY, who has emphasized this fact, has also shown that in congenital dislocation of the hip, the anteversion of the femoral neck is constantly enhanced. As is well known, he has brought forward reasons to assume that this exaggerated anteversion is due to enhanced leverage of the femur on the pelvic border caused by enhanced pressure from too small an amniotic sac against the bent legs of the foetus—we are under the impression that anteversion of the femoral neck develops more easily than deformation in the direction of functional pressure, for example, than Coxa vara. In other words, *bone seems to possess greater plasticity to twisting forces than to functional pressure.* If this be correct, it is in agreement with the fact described in the previous chapter, viz., that bone gives way to pressure acting at right angles to the direction of functional pressure sooner than to pressure acting in this direction. All distorting forces, indeed, have a component acting at right angles to functional pressure.

The external forces of function (and even the more constant pressure stresses whose direction coincides with that of function) are related to the internal forces which produce bone, as polar magnitudes. If the internal forces of bone formation are insufficient, either relatively or absolutely, so that the external forces cause a change of the external form, we observe that the bone cells, so to speak, exert themselves to check the evil consequences by a modification of the course and width of the elements—possibly also of the quantity of lime salts contained in them—corresponding with the new course and intensity of the pressure stresses, and thus to enable the bone to meet the new mechanical exigencies. This is the process first demonstrated by WOLFF with beautiful figures, and called " transformation " That the primary change of the external form, which was brought about by external forces—and which, secondarily, leads to " transformation," *i.e.*, to modification of the internal structure—was unjustly called " transformation " by WOLFF, and thus attributed to internal forces as well as the internal changes, has been clearly shown by LORENZ.

Besides after changes of the external form the phenomenon of "transformation" also manifests itself—as was shown in the previous chapters—in bones whose external form is preserved whilst the acting forces are modified, as in ankylosed joints (Fig. 16—20, 33—35). And *besides in all these pathological conditions it may be assumed that also in normal bones* changes in the direction of the bone elements are constantly going on, both during growth and on such modifications of the external form as lie within normal limits, for instance, the normal anteversio colli femoris, which increases in the last months of intra-uterine life and decreases after birth (LE DAMANY).

If this assumption be correct, these normal changes in the internal structure of bones have to be reckoned among the phenomena of "transformation," since they correspond with changes in functional stresses, or, reversely, transformation is to be considered as a process of normal growth which becomes manifest when the form or function of bone is abnormal.

Summing up, "transformation" is the outcome of the fact that the bone elements, which on a given form of the bones coincide with the directions of functional pressure stresses, change their course and width—and possibly the quantity of lime salts—whenever the course and intensity of these stresses change, so as to make them answer their purpose again. It implies the atrophy and demolition of some elements of cancellous bone, the thickening and formation of others.

Instead of WOLFF'S "law of transformation" of bones, the following rule may be considered to be established :—

The form of bones being given, the bone elements place or displace themselves in the direction of functional pressure. This may be considered as the only tenable remnant of that "law." But it must here be emphasized that the external form of the bones is (quite apart from their internal structure, their cancellous tissue) not determined by functional pressure only as may become evident in the following Chapter.

CHAPTER VII.

LIMITS TO THE POWER OF FUNCTIONAL PRESSURE.

The previous chapters may have shown that functional pressure exerts a trophic stimulus on bone tissue, even to such an extent that the direction and mutual arrangement of the bone elements largely corresponds with the direction and mutual arrangement of pressure stresses which are transmitted by them during function. This might raise the thought that the formation of bone tissue is absolutely bound to the action of pressure; that the origin as well as the existence of bone tissue are dependent on pressure, so that bone tissue could appear only where pressure acts and would have to disappear where pressure stresses cease to make themselves felt.

We have mentioned in the above that indeed WOLFF and ROUX[1] have taught that bones both in normal and pathological conditions have a "functional," "mathematical form," that, in other words, functional forces entirely and exclusively determine the form—as well as the structure—of bones mechanically,[2] mathematically, both under normal and pathological conditions.

They ascribed the power of bone formation to *tension* as well as to pressure, and in the previous chapters it may have become evident that this was done on untenable grounds. Hence the doctrine of the "functional," "mathematical" form of the bones could for the present be taken only in the sense that only pressure stresses determine the form of bones with mathematical accuracy.

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[1] JULIUS WOLFF, l.c. p. 90 ff.

Id., Die Lehre von der functionellen Knochengestalt. VIRCHOW'S Archiv. Bd. CL.

[2] Id., l.c. p. 146.

It is evident that this doctrine of the "functional," "mathematical" form of the bones implies that each unit of functional pressure should answer to a unit of bone of definite length and width; and that from the mathematical synthesis of these bone units, both the form and the size of the bones should result. This unit, however, has never been determined. In the previous pages, when discussing the length of the forelegs and the neck of the giraffe and the legs of birds (see p. 79), we deemed it probable that besides mechanical agents other factors also have had a share in determining the length, as also the width, of the bones. And in the following pages we shall see that wherever we observe phenomena of bone formation, even when they may be attributed to pressure stresses, we are at the same time struck by the activity of other agents which cannot be reduced to mechanical forces. In order to give evidence of this statement, we will consider the effect of functional pressure on *bone formation* and *on the form of bones* separately.

A. On bone formation.

ZSCHOKKE[1] found in an overgrowth—pelvis fragments and the bones of a hind leg of a cow—unmistakable cancellous tissue, without muscles being present. Although the structure of this cancellous tissue differed from the normal, yet from its presence, as well as from the presence of the bones as such, it becomes evident that the formation of cancellous tissue and of bone in general can take place independent of the action of pressure.

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[1] l.c. p. 51.

In man we also find examples of bone formation independent of functional pressure. When, for instance, shortly after birth an extremity is struck by infantile paralysis, and remains devoid of any functional pressure, being a worthless appendage, we nevertheless find the bones maintained—largely even in their normal form, although they are much lighter and more flexible, and have especially thin cancellous tissue so that slight pressure may bend or even break them. Moreover, growth lags behind the normal. If with regard to this fact we may leave out of consideration the trophic changes in consequence of paralysis of nerves in such an extremity, its bones show the extreme of which hereditary forces are capable without the aid of functional pressure. The difference of the bones in such an extremity then would indicate the part of (growth and) bone formation which must be attributed to functional pressure. And if changes due to the trophic influence of nerves (caused by their paralysis) may not be left out of consideration, *more* bone formation might be expected so that the maintainance (and even growth) of the totally paralysed extremity is the obvious proof of the fact that bone formation independent of mechanical stresses—or shortly, *independent bone formation*—is a hereditary power of man.

In apparent contradiction with the development of cancellous tissue in an overgrowth in which pressure stresses are lacking, is the rarefaction or the almost total disappearance of cancellous tissue which we observed in our research on bones of the extremities and vertebral bodies, wherever pressure stresses had ceased to act. This raises the thought that the hereditary power of *independent bone formation* is not preserved in the same degree during the whole of life, but decreases after the period of primary formation and growth. In other words, *cancellous tissue seems to become more dependent on pressure stresses during* *its existence than it is at the time of its primary formation and growth.*

In later periods of life periosteal bone also seems less dependent on functional pressure than cancellous tissue. In the bone sections examined by us, the periosteal bone tube has been preserved thicker than the contiguous cancellous tissue, so that, for instance, in the ankylosed knee (Fig. 33), the original external form of femur and tibia is maintained by a periosteal bony shell—be it a thin one—whilst the cancellous tissue situated more centrally has almost entirely disappeared. The re-formation of bones after subperiosteal removal (tube-bones, ribs) gives evidence of the fact that in the periosteum, *even in the adult, the power of independent bone formation is present.* Indeed, before the periosteum has formed a tube or rod of a certain firmness, the trophic effect of functional pressure can be excluded—at least in the tube bones.

In a further way the periosteum shows itself capable of independent bone formation. SCHAUTA—directed by BRÜCKE—laid open the fascia lata in a rabbit, two or three days old, over the entire length of the right femur, and found that bone after two months a good deal thicker (and a little shorter) than the left one. In a dog, a cat, and a pig, two or three weeks old, he extirpated an eye and after some time he found the wall of the orbit and the maxilla thickened. A similar observation was made by SCHROEDER VAN DER KOLK, who in hemiatrophia cerebri sinistra found the posterior part of the skull on that side thickened.[1] Whether, besides a diminution of the pressure as such, also a distension of the vessels and increased afflux of blood exert an influence, we will leave undecided. What cells have the greatest share in this bone formation may also be left out of discussion. The chief point for the present is that the periosteum, both of the femur and of the skull, appear to be capable of bone formation without an increase of pressure.

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[1] SCHROEDER VAN DER KOLK, Waarneming eener atrophie van het linker halfrond der hersenen. Amsterdam, J. SULPKE, 1852.

Numerous experiments with periosteum and bone tissue on animals, made by a number of investigators and lately repeated with ingenious modifications by MEYER and WEHNER,[1] have also shown that, not only the periosteum, but also the endosteum and the walls of the Haversian canals are capable of bone formation after being stripped of the trophic stimulus of function, and even when, after transplantation, they are dependent on their new surroundings. However, *the power of independent bone formation seems to be most highly developed in the periosteum.*

Independent bone formation has recently become of considerable importance. It manifests itself in bone transplants which of late years have rendered valuable services in the treatment of deformities.[2] In them bone formation may be expected, especially from the periosteum, even when functional pressure is lacking. Yet the trophic effect of functional pressure should not be underrated or neglected. In the future differences in the power of independent bone formation between various skeletal parts may possibly be taken into consideration. So in cases where little or no functional pressure can be expected from the new surroundings of the transplant, bones may possibly be selected as transplants in which the power of independent bone formation is highly developed.

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[1] LEO MAYER a. ERNST WEHNER. An experimental study on osteogenesis.—The American Journal of Orthopædic Surgery. Vol. II, No. 2, p. 213.

[2] FRED H. ALBEE, Bone graft surgery, l.c.

ROBERT JONES, Notes on Military Orthopædics, l.c.

CHARLES DANISON and FRANKLIN D. SMITH, Autoplastic Bone Surgery. LEA and FOBIGER, Philadelphia and New York, 1917.

S. VORONOFF, Traité des greffes humaines. (Greffes osseuses et articulaires.) Octave Doin et fils, Paris, 1916.

Besides being of practical utility independent bone formation is also of theoretical importance. If we wish to form an idea of its causes, two groups of phenomena have to be distinguished. In animals, and even in the lower ones, the skeleton shows the double function of *support* (to the organs of motion) and of *protection* (to tender, regulating, directing organs as the central nervous system and the special senses). As is well known a number of natural philosophers tend to assume that each organ has been brought about by its function.[1] With regard to the bones of the extremities and the vertebral bodies, indeed, the idea seems justified that functional pressure has preceded the origin of these bones, and that independent bone formation—inasmuch as they show it—forms the hereditary product of such pressure. This, however, is not equally applicable to bones in which the protecting function seems to be the primary one, as is the case with the cranium, vertebral arches, and to a certain extent also with the bones of the face, products of the branchial arches and the ribs. We have tried to prove in the above (See Chapter II, B2) that the origin of the cranium in which the protecting function seems to be most obvious, cannot be justly attributed to the action of the mechanical forces (see pp. 28-30 and pp. 82 and 83). Hence we are led to assume that the ossification of the cranium has been brought about independent of, and before, the action of mechanical forces, which in the absence of the bone would have threatened not only the underlying soft parts but at the same time the existence of the individual, or would have rendered its life impossible. In other words, the formation of the cranium seems comparable to the formation of the hard shell round molluscs. The delicate brain cells seem to have surrounded themselves with a scale of firm tissue not unlike the caterpillar, which forms a wrapping out of morsels of bark, even before external forces are acting to threaten it either with injury or destruction.

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[1] Cf. f.i. POIRIER, Anatomie T. I p. 4. " L'horizon s'est singulièrement agrandi. . . depuis qu'il est devenu évident pour tout anatomiste que l'organe est créé par sa fonction même''. . . Cette vérité est la base de la théorie transformiste.

These are all mere considerations, the purport of which we do not wish to overrate. Yet it may have become patent that inasmuch as we are entitled to speak of protecting bones, we are not justified to assume that external mechanical forces have formed the functional stimulus for their first origin, any more than that the independent bone formation which these bones show, is the hereditary effect of such mechanical forces. On the other hand, both these assumptions seem justified—at any rate to a certain extent—with regard to supporting bones. Hence in protecting bones the formation of bone seems from the very beginning to have been less dependent on mechanical forces than in supporting bones, if a distinction between supporting and protecting bones may be made at all.

In this connection it may be of importance that during the development of the spine in the foetus, *the first central centres of ossification appear in the middle of the spine*—the 6th to the 12th vertebral bodies[1]—whereas the (anterior and posterior) *neural* centres of ossification (of the vertebral arches) as well as the bone centres of the transverse processes, which appear a little later, *first appear in the cranial part of the spine* and after that successively in the vertebræ situated more caudally.[1] So the ossification centres of the vertebral bodies, in which the supporting function plays an active part, first appear where the greatest stresses may be assumed to develop, whilst the ossification of the neural elements of the spine in which the supporting function is less obvious in contrast with the protecting function, takes place in the order of primary formation of the parts. Of course we lack any certainty about the essential meaning of the difference between axial and neural vertebral parts in the order of their ossification. Nevertheless *it is in agreement with the assumption that bone formation is more independent of mechanical forces, whenever the protecting function stands in the foreground, more dependent on mechanical forces, whenever the supporting function is the primary one.*

But whatever be the notions we attach to the facts, observation teaches that *boneformation sometimes takes*

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[1] Cf. Poirier, Anatomie. T. I p. 383.

place in connection with functional pressure—as may have become evident in the previous chapter—*sometimes also without any pressure* (or mechanical stress) being responsible. And with this recognition we have come *to the limits to the effect of pressure on boneformation, i.e.*, to phenemena in the life of bone tissue which cannot be attributed to mechanical stresses as primary agents.

However, it is not only in independent boneformation that non-mechanical factors have a share. Boneformation, by pressure stresses as such, is a phenomenon which does not admit of a mechanical explanation. That living mesoblast cells respond to pressure stresses by the formation of an intercellular substance, fit to resist not only these pressure stresses, but even the tension stresses in the direction of these pressure stresses as well as in directions at right angles to them—so that compression phenomena as well as transverse and longitudinal fissures (KRÖNLEIN'S fractures) are rare occurrences—is an adequate performance which we have not learned to resolve into mechanical factors. This also applies to the fact that the bone elements place themselves in—and eventually change with—the directions of pressure, the phenomena we have dealt with in the study of the formation, the structure and the "transformation" of cancellous tissue.

We shall meet with some more examples in the life of bone tissue of such phenomena as cannot be reduced to mechanical factors in the following pages, where we will try to trace the effect of pressure stresses on the *form* of bones.

B. On the form of bones.

The condylar or tuberal enlargement of the articular ends of the tube bones in which we were led to see the cause of the cancellous structure (p. 51), is in its turn not to be reduced to a mechanical cause. It is *useful, adequate*, because it ensures *greater stability* to the contiguous joints. We see this thickening most developed in the knee-joint, in a frontal direction in which the chance of undesired movements, *i.e.*, in planes other than that of flexion, is greatest. In the usefulness, adequacy, of a quality scientists are often inclined to see a ground for its preservation and its heredity. Some may also find in the adequacy of the primary thickening as such a ground for its origin. Others may consider it a "casual" variation, just as well as the origin of species—and even of life in general—is often considered a consequence of casual meetings of atoms. These assumptions, however, reduce neither the origin nor the maintainance of the terminal thickening of tube-bones to mechanical forces. This equally applies to the cancellous structure as such in these articular ends: the demolition of bone which is not made to bear pressure, is a useful process suggestive of *economy*. The absence of pressure stresses, which leads to the disappearance of bone tissue, cannot be alleged as the mere cause of such disappearance: a foundation does not disappear when the house ceases to bear weight on it. The indisputable condition for the demolition of bone elements which have ceased to bear weight, is *the activity of living cells which has not been resolved into mechanical factors*. However, the disappearance of bone which ceases to bear weight—and with it the formation of cancellous tissue—concerns the structure of bone rather than the form of bones which is now under discussion.

The *tube form* ensures—as has been observed in the above—the greatest possible firmness against bending with a minimum of material. Besides in man or animals, we frequently meet with it in plants (halms). In bones which are short with regard to the area of the joint surfaces, the tube form is failing, and the cancellous structure of the articular ends is retained over the whole length of the bones (vertebral bodies, carpal and tarsal bones); whereas in bones which are long with regard to the transverse section, so that weight bearing is liable to make them bend, the cancellous ends blend in the middle of the bone to a tube of compact bone. In the ribs in which indeed the length is greatest with regard to the transverse section and which thus occupy the very first place among the long bones, we find the tube shape failing. In them, however, there is no question of weight bearing being a cause of bending by functional pressure acting in opposite directions at both ends, but rather of a pressure—equal to the difference between atmospheric and intrathoracic pressure—acting at right angles to the external surface, *i.e.*, to the thoracic wall. Hence *the tube form seems to be dependent on the bending of bone by endwise weight bearing. The fact, however, that the arrangement of the material appears to be most adequate to withstand such weight bearing, is anything but a mechanical explanation for such arrangement.*

Whenever tendons wind around bones with a sharp curve, thus on the one hand becoming themselves exposed to functional pressure, on the other hand also exposing the surface of the bone to such pressure at the place of contact, we saw (in Chapter V.) bone develops either in the tendons (sesamoid bones) or below them as *prominences* on the bone (trochanters of femur, tuberosity of radius), which are directed at right angles to the traction (ZSCHOKKE), *i.e.*, against the pressure. That in some cases a sesamoid bone develops, in others a tuberosity, is again a phenomenon for which a *mechanical explanation cannot be given.*

Where numerous muscle bundles need to be fastened to the bone, we see prominences develop on the bones which are upon the whole directed at right or oblique angles to the traction of the muscles, so that on contraction of the muscles they are made to bend. This is most evident in the processes of the vertebræ in which, on account of the attachment of numerous muscles, the bending can take place in many directions, and hence both tension and pressure stresses can be evoked. Not always, however, do we meet with bony prominences, when a large number of muscle bundles demands origin or insertion. We often find tendon tissue starting from the bone, a phenomenon which is especially evident in the case of the strong, distating muscles[1] (of which M. quadriceps and M. soleus are the most striking examples). The tendinous tissue then naturally coincides far more nearly with the direction of the muscle bundles than do the bony processes. Now, why bony processes develop on the vertebræ, whilst tendinous tissue takes origin from femur, tibia and fibula, though both seem to be intended for the enlargement of the area of attachment for the numerous muscle bundles, cannot be explained by mechanical forces. Can we forbear seeing adequacy in the arrangements described? Would not flexion of the knee be disturbed if bony processes instead of tendinous tissue should develop at the back of the femur, tibia and fibula? On the other hand, if the vertebral processes should be substituted by tendinous tissue, would not too short lever arms and too short muscle fibres in the muscles of the back limit the mobility of the spine? However, even an affirmative answer to these questions is far from being equal to a mechanical explanation. Not for all bony protrusions is it evident that they are bent by muscle contraction. The protrusion, for instance, which may develop at the site of insertion of tendons and in the tendons of old people, as well as numerous bony excrescences prove that besides mechanical, viz., pressure stresses, other factors also have a share in the formation of bone and in determining the form of bones. Each of those growths will demand special research to secure a proper insight into its meçhanical relations, which however, lies outside the scope of this study. Yet we may observe that they cannot be used as proofs that tension stresses lead to bone formation, since these growths often fail to appear though the mechanical conditions are the same.

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[1] C.f. MURK JANSEN, Ueber die Länge der Muskelbündel und ihre Bedeutung für die Entstehung der spastischen Kontrakturen, F. ENKE, Stuttgart, 1916; and in D. Zeitschr. f. Orth. Chir. Bd. XXXVI.

In the previous chapters we tried to prove that the external forces which act on supporting bones, being given, functional pressure roughly determines their internal structure. In this chapter it may have become evident that *neither boneformation nor the form of the bones is determined solely by functional pressure.* Even if we were entitled to assume that a definite unit of functional pressure causes a unit of bone of definite length and width to develop, and if moreover this unit should be known, even then the mathematical synthesis of the required bone units would not lead to the existing form of the bones. *A kind of "intellectual judgment" would be required to model a tube form in one place, an articular widening and cancellous tissue in another, to decide elsewhere whether a bony protrusion or a tendinous appendage was to come into existence, a tuberosity or a sesamoid bone, in order that firm, light, in short, appropriate instruments of support and movement should result. And in protecting bones*—inasmuch as they may be considered to exist—*a similar "judgment" would be required even before the action of pressure stresses.*

But even if we should be mistaken, *i.e.*, if to functional stresses the power might be ascribed to make all these special decisions for the appropriate form of the bones, even then *the form of the bones might not be called "mathematical" or functional," because there are still more agents which make their influence felt upon it.*

In the first place there is the fact *that bones are capable of resisting greater forces than those which act during their formation* (ZSCHOKKE), a fact which reveals the activity of a non-mechanical factor determining the strength—the width—of the bone elements.

In the second place there are *the roundings and excavations of the bones caused by slight pressure of contiguous soft parts* in a lateral direction, *i.e.*, in directions at right angles to that of functional pressure (see Chapter V). They constitute as many deviations from the mathematical form of the bones, because they are due to the "casual" presence of these parts, *i.e.*, to a slight pressure that is not essentially related to functional pressure.

Finally, in the third place there is the phenomenon of *independent boneformation*, which—as was seen in Chapter VII. (A)—has its share in determining the form of the bones, as, for instance, after the extirpation of an eye, the cleaving of a fascia. Equally independent of functional pressure is the formation of bone which may be observed on the transplantation of particles of bone or periosteum into soft parts, for instance, in the abdominal wall (heterotopic bone transplantation).

And the fact that the cudgel-shaped thickening of the articular ends is maintained in the ankylosed knee, in which a periosteal boneshell is preserved better than the contiguous atrophic cancellous tissue, suggests the activity of hereditary forces which ensure the appropriate cudgel-shape of the bone ends, even after the purpose of this thickening has been done away with by the bony union of the articular ends. In other words, it proves that even in the transformation of the bones—in contrast with WOLFF'S law—other than mechanical factors make themselves felt.

In short, different phenomena in connection with the form of the bones, the surplus of stability and the phenomenon of independent bone formation, all show that in the life of bone tissue besides functional pressure other agents are acting.

Thus our investigation may have led us to assume:

(1) That tension has no power of boneformation, so that CULMANN-MEYER-WOLFF-ROUX's doctrine of the trajectorial structure of the bones, and WOLFF's "law" of the transformation of the bones—which ascribed the same power to tension as well as to pressure—have to be relinquished. (Chapters II. and III.)

(2) That functional pressure is indeed an important factor in boneformation, so much so that, the form of the bones being given, the bone elements place (or displace) themselves in its varied directions, regulating their width after the intensity of the pressure, and that, both in normal and in deformed bones cancellous tissue appears to be composed of such pressure elements (Chapter IV. and V.);

(3) That functional pressure is not the only and omnipotent factor determining boneformation and the form of bones, and that WOLFF-ROUX's doctrine of the "mathematical" "functional" form of the bones is untenable, because besides mechanical pressure other factors make themselves felt in the formation of bone as well as on the form of bones. (Chapter VII.)

It will be the object of the following and last chapter of this study to trace the nature of these factors.

CHAPTER VIII.

PURPOSIVE FACTORS IN BONEFORMATION.

If we consider the skeleton as having been "created by its proper function"[1] this creation cannot be denied to be an "appropriate" one, or also: if we consider the skeleton to be the outcome of a struggle between protoplasmic elements on the one hand and pressure stresses on the other, it must be equally admitted that this struggle is fought in an appropriate manner and—under normal conditions—decided in favour of the protoplasmic elements. In the nature of the intercellular substance which does not only resist pressure but also tension even in directions at right angles to the pressure; in the direction of the bone elements, coinciding with the direction of the lines of pressure and eventually shifting with them (transformation); in the surplus of firmness through which forces can be resisted which surpass the normal; in the presence of the same material—as if for protection—round tender, perceptive and regulating organs; in the "yielding" to the soft sister tissues, sometimes going even so far as to become fatal to the bone tissue itself; in the tube form of the bones which are submitted to flexion by weight bearing; in the cudgel-shaped thickening of the articular ends of these bones; in the cancellous structure wheresoever the transmission of the pressure stresses takes place through relatively large cross sections; in the formation of processes for the attachment of organs of motion, we see as many "appropriate" arrangements, *i.e.*, arrangements by which the bones answer their purpose.

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[1] Cf. Poirier, l.c., T. I., p. 4.

We are fully aware we have not summed up all appropriate arrangements by any means. Various skeletal parts, indeed, as the pelvis and the shoulder girdle, as well as a number of parts of the skeleton, have been entirely left out of consideration. Is not, for instance, the presence of incisors and molars in the jaws a phenomenon of the same nature? And does not this also apply to the cartilage layer of articular surfaces which maintains itself, although being exposed to the same stresses as the contiguous cancellous tissue which is constructed entirely in correspondence with these stresses?

Nor do we imagine to give an explanation of the phenomenon by the use of the term "appropriate." *With it we only express that the dealings of the bone cells in the human body show a similarity with the dealings of our own judgment, such as they manifest themselves in the making of objects for our use outside the body.* Just as our implements around us show "appropriate" constructions, so do the skeletal parts inside the body. It is through these "appropriate" arrangements that both groups to our judgment answer their purpose. In the making of both groups of implements—the skeletal parts inside, the objects for daily use outside the body—purposive factors seem to have been acting.

Many scientists object to seeing and recognising "purposive" factors in nature.

Some are afraid that the recognition of such factors endangers the mechanical explanation of phenomena—usually (and exclusively) called "causal" explanation. This book may give evidence of the fact, that, on the contrary, the mechanical consideration of biological phenomena—which was made in the first six chapters—is fully compatible with the recognition of purposive factors, the study of which was initiated in the seventh and eight chapters. The tracing of the effect of mechanical stresses in living bodies and the tracing of purposive factors are two ways of viewing things, independent of each other, like two methods of research, as, for instance, weighing and measuring. Just as a body after being measured may also be weighed, so may phenomena which have been examined mechanically also be tested with regard to the degree in which—to our judgment—they answer their purpose. And reversely, it may be attempted to resolve phenomena which we call "appropriate" into mechanical elements. *Indeed we recognise an appropriate arrangement in the parallelism which the first chapters showed between bone formation and pressure stresses, although we have not felt able reversely to resolve into mechanical elements the purposive factors, the outcome of which we have dealt with in this chapter.*

Some scientists object to the recognition of "purposive factors" in nature because they also meet with inappropriate arrangements.[1] They fail to see that the recognition of "inappropriate arrangements" implies the application of the same method of investigation, and means the completion of the method rather than its subversion.

Others are of the opinion that the term "appro_ priateness" reveals a certain arrogance on the part of the biologist. We cannot share this opinion either: *No one will hesitate to apply the term "appropriate" to those acts of living cells which are carried out consciously*—as, for instance, the making of utensils. Thus the question arises: Are we for modesty's sake to stop with conscious acts in asking after the purpose? In other words, is the term "appropriateness" indeed to be restricted to conscious acts of the human body? Are we wrong in inquiring after the purpose of acts of live cells as soon as they form no part of conscious dealings, and immodest in trying to determine their greater or lesser degree of appropriateness? May, for instance, the co-ordination of our movements not be termed "appropriate" because it is carried out unconsciously? Nobody will be charged with arrogance for admitting that the co-ordination of movements, though performed unconsciously, is "appropriate," *i.e.*, answers their purpose, and even that movements are led by "purposive factors." Hence the term "appropriate" may be justly extended to unconscious acts. The two groups of acts under discussion are led by ganglion cells, which occupy a special position among living cells, because in them the power of forming and fixing conceptions—a power which may be briefly called *the power of knowing and learning*—is admitted by most investigators. Hence the question arises: *May the carrying out of appropriate acts be restricted to a special kind of cells, the ganglion cells*? A simple reasoning will show that this is not the case.

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[1] Cf. F. C. F. C. Went, Ondoelmatigheid in de levende natuur. Utrecht, 1906.

For those who adopt the doctrine of evolution, the origin of higher organisms has gone hand in hand with a *division of labour*, which has been recognised as a natural law by MILNE EDWARDS, and by which each of the cell-groups into which the lower organism splits up, develops a special function to a higher level without however losing the other functions altogether. While, for instance, the mesoblastic cells develop the power of producing material for support to a higher degree of perfection, this power is not entirely lost in the epithelial elements: these also develop their hyaline membrane as such (GEGENBAUR). This justifies the conception that *whilst in the ganglion cells the power of learning and knowing is developed to a higher degree of perfection, this power is not entirely lost in the other body cells.*

Be this as it may, it is certain that the power of fixing conceptions, *i.e.*, of learning and knowing cannot justly be considered to be restricted to ganglion cells. The method of the division of labour in the development of higher organisms renders it probable that the bone cells have this power as well, even if it be in a more limited measure, as the ganglion cells. The bone cells seem to have used this power in the development of the species, and to show it by inheritance in the development of the individual. Hence if appropriate acts are bound to the power of knowing and learning, the unconscious appropriate acts of the bone cells need not surprise us any more than the appropriate—either conscious or unconscious—acts of the ganglion cells. And it must be considered arbitrary to ascribe to ganglion cells a power of performing appropriate acts and to deny this power to bone cells. Thus the doctrine of evolution leads us to assume that in bone cells there is some of the power of learning and knowing, of which we feel unconscious, whilst we are said to be conscious of its presence in ganglion cells.

The same train of thought must have led BERGSON[1] when he established the law: "When a tendency splits up its development, each of the special tendencies which are born from it, tend to preserve and develop from the original tendency all that is not incompatible with the work for which it is specialised."

But whether we adopt the doctrine of evolution and with it the division of labour among the different cell groups—with a higher development of a special faculty and at the same time the preservation of part of the original faculties—we cannot escape from the conception that in the phenomena of life a something acts a part "that carries the purpose in itself" (ὃ ἔχει ἐν ἑαυτῷ τὸ τέλος), that we may call "entelechie"[1] a word taken from Aristotle—and that is not open to a mechanical explanation any more than the phenomena of our judgment. Does not every scientist see in all that lives a "*striving*" *for the preservation of the individual*, a striving for the preservation of the species, and do not many also see a *striving for higher perfection? And is not all "striving" directed to a purpose?* Indeed, after ARISTOTLE, universal intellects as GALILEO, NEWTON, LEIBNITZ, KANT, v. HARTMANN, and others have recognised purposive factors in nature.

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[1] HENRI BERGSON, L'évolution créatrice, p. 129, 19ième édition, Paris, 1916.

All acts of the bone cells that we observed in connection with the formation of bone and with the form of bones —both those of the first chapters which showed a parallelism with pressure stresses, and those under discussion in the last two chapters, which appeared to be more independent of pressure stresses—*seem to us to be directed to the same purpose, the providing of support and protection for the preservation of the individual. For this purpose, mechanical though it be, the bone cells seem to strive with means and in ways which show similarity with the means and ways which our judgment would adopt.*

These means may upon the whole be mechanical ones, and show a parallelism with mechanical—viz., pressure—

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[1] H. DRIESCH, Philosophie des Organischen (Gifford-Vorlesungen, Aberdeen), I. Bd. p. 145. Cf. also T. E. HERING, Ueber das Gedächtnis als eine allgemeine Funktion der organischen Materie, 1870.

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stresses, the agents under whose rule they are, which are sensitive to mechanical stimuli, which select the suitable material from the nutritive liquids, which construct the solid bars placing or displacing them in adequate directions, which make prominences and excavations and many other useful arrangements; these agents do not for the present admit of mechanical analysis. Will they ever?

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